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Roseborough et al.

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[54] **CREATURE ANIMATION AND SIMULATION TECHNIQUE**

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[73] Assignees: **James B. Roseborough**, San Francisco; **Timothy Kostolansky**, Oakland, both of Calif.

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[51] **Int. Cl.**7 .... **G06T 15/00**

[52] **U.S. Cl.** **345/473**

[58] **Field of Search** 345/473, 474

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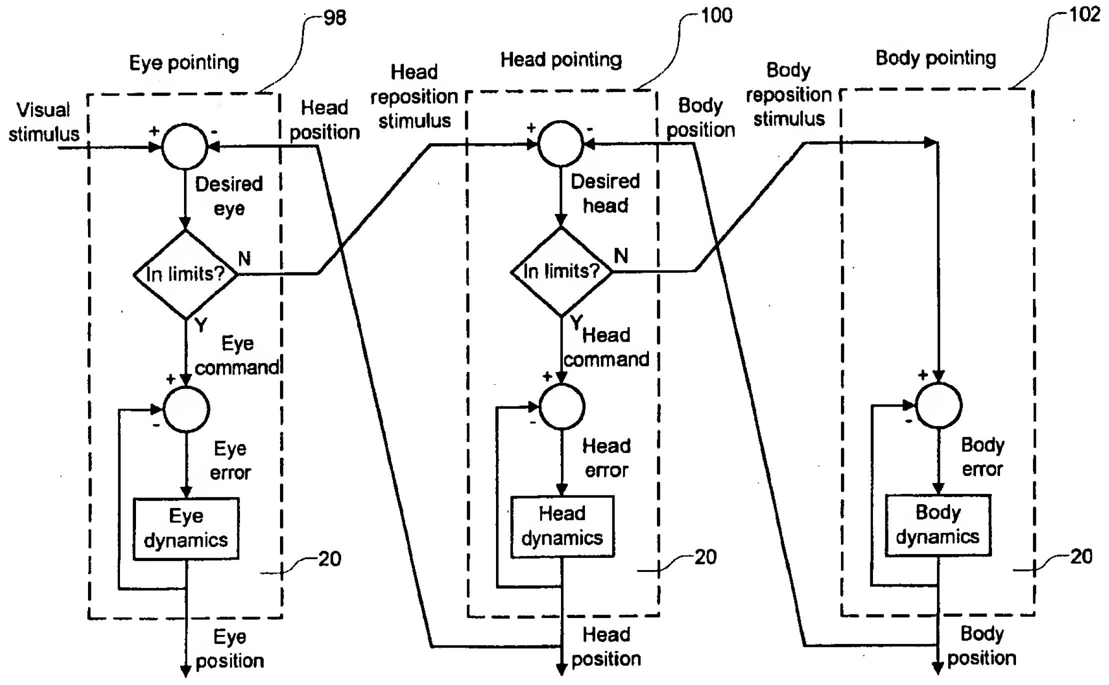
Assistant Examiner—Cliff N. Vo
Attorney, Agent, or Firm—Hickman Stephens Coleman & Hughes, LLP

[57] **ABSTRACT**

A synthetic creature (10) in which links (26), representing limbs, are loosely connected by joints (28) to independently interact and implement the physics of everyday life-like actions (18) in a character (16). Elements of mass, positive weight (46), and negative weight (48) are independently handled to mimic the closed-loop control characteristics of real animals. The synthetic creature (10) uses intelligent appearing behaviors (20) built up out of the actions (18) and recursively arranged in a hierarchical behavior tree (72) to cooperate and compete in a run-time computer (202) to give a feeling of autonomy and awareness. Further taught is an authoring environment (200) of tools used to author the character (16), actions (18), and behaviors (20) of the synthetic creature (10), which provide author feedback and simulation testing capability at the various layers (12) of the synthetic creature (10).

24 Claims, 20 Drawing Sheets



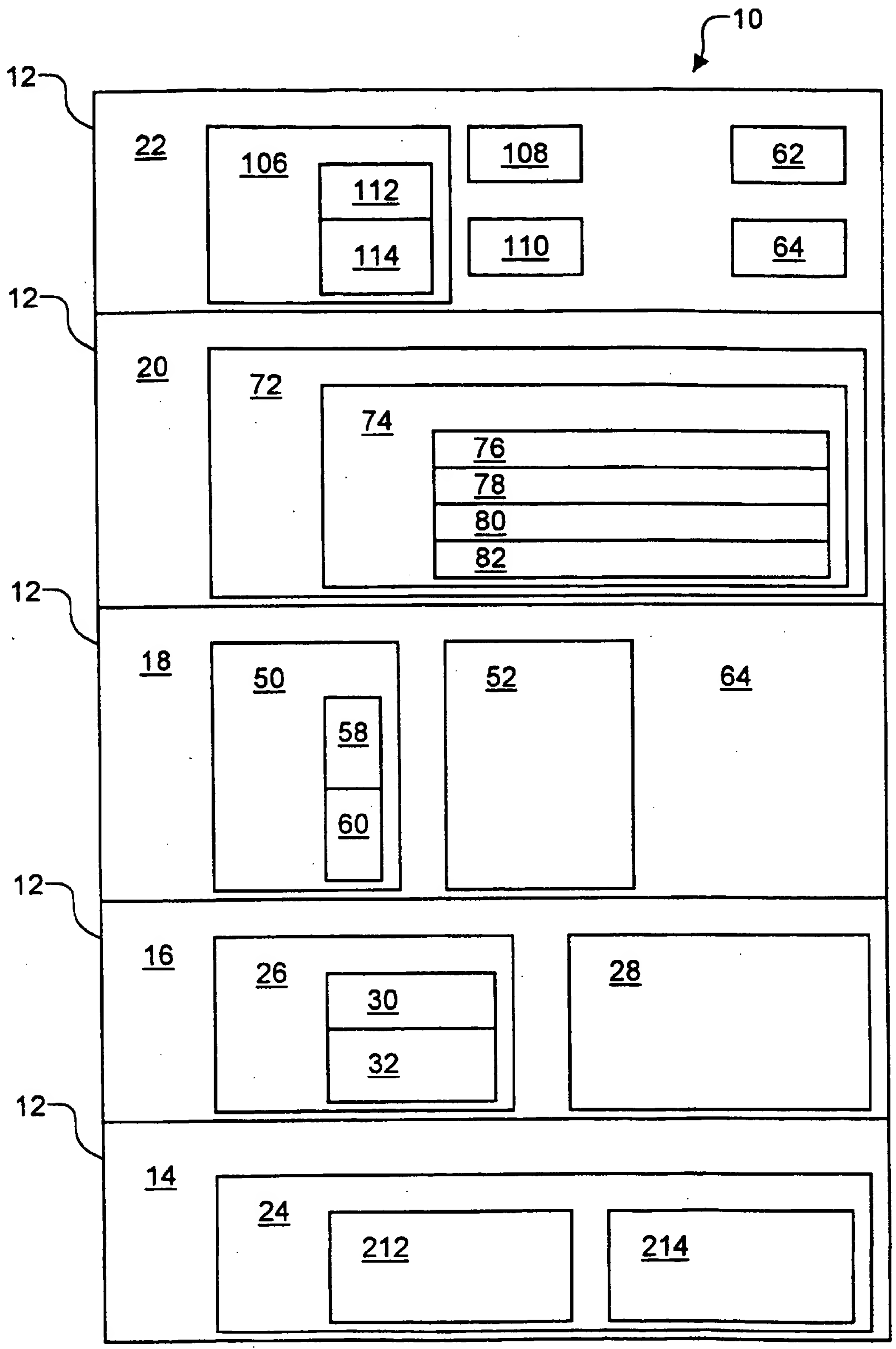

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FIG. 1

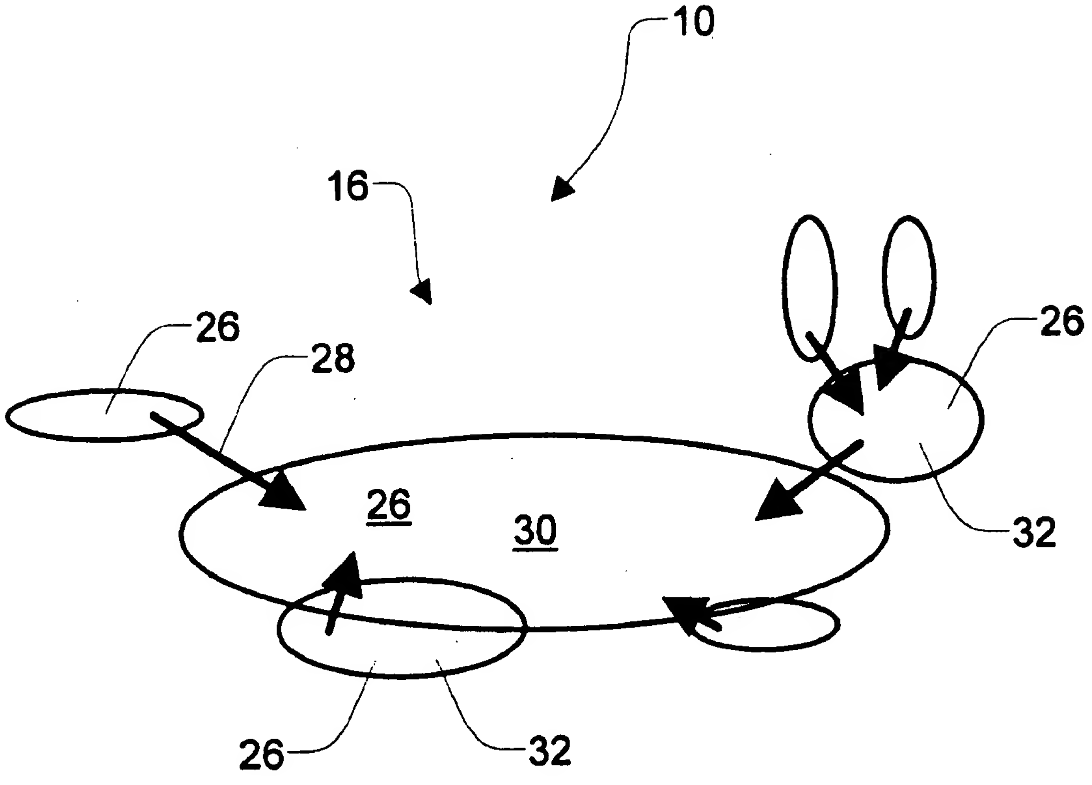


FIG. 2

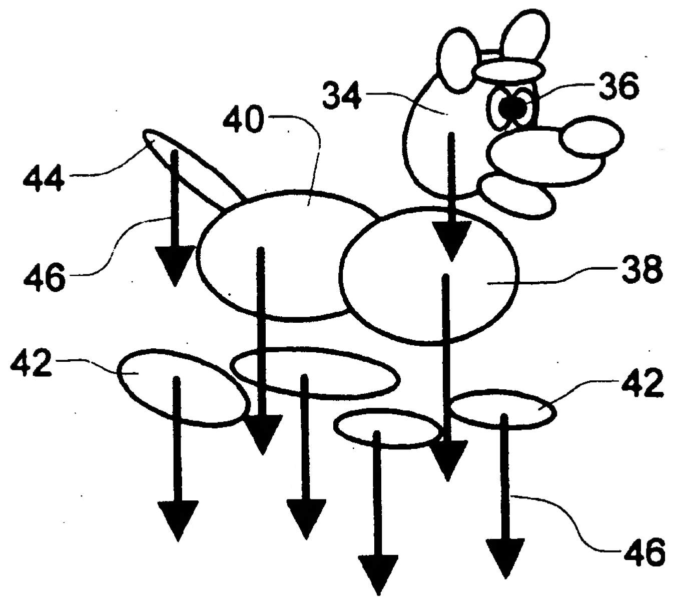


FIG. 3

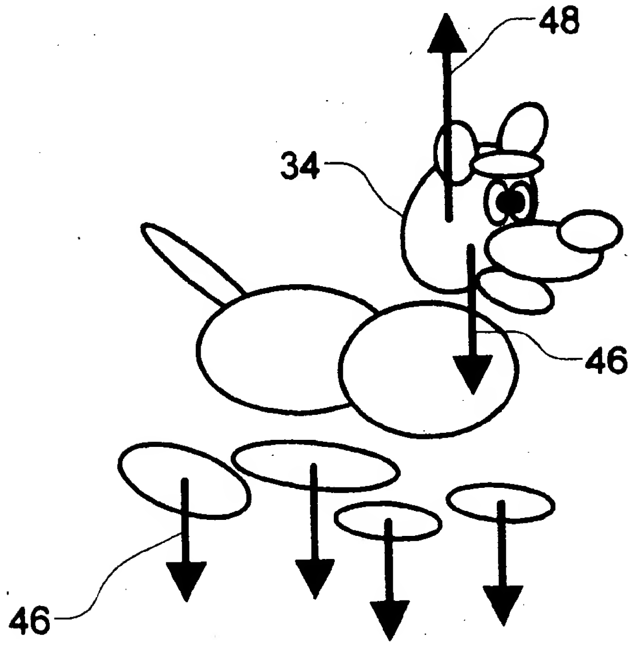
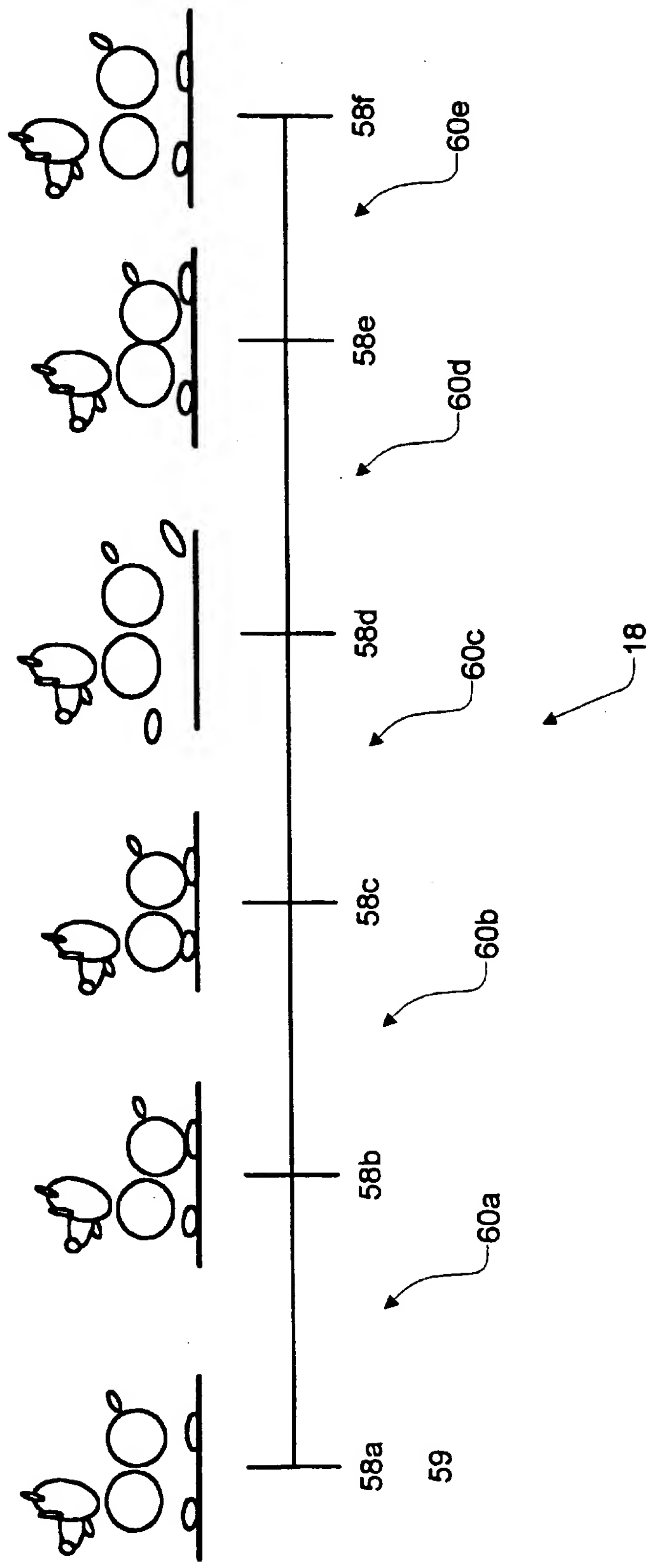
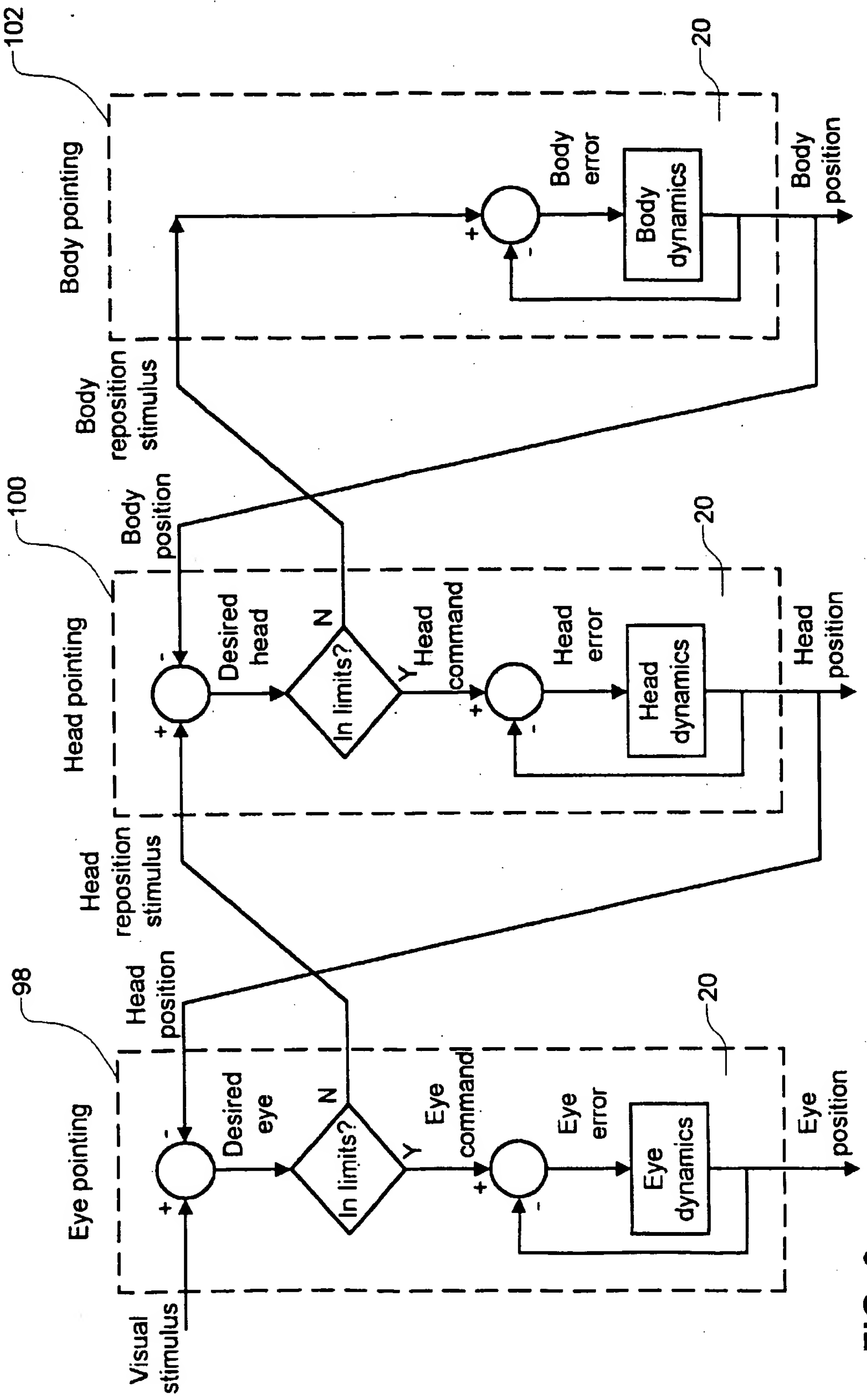


FIG. 4

FIG. 5

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98
Visual stimulus
+
-
Desired eye
In limits?
N
Y
Eye command
+
-
Eye error
Eye dynamics
Eye position
20
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Head reposition stimulus
Head pointing
100
+
-
Desired head
In limits?
N
Y
Head command
+
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Body dynamics
Body position
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FIG. 6

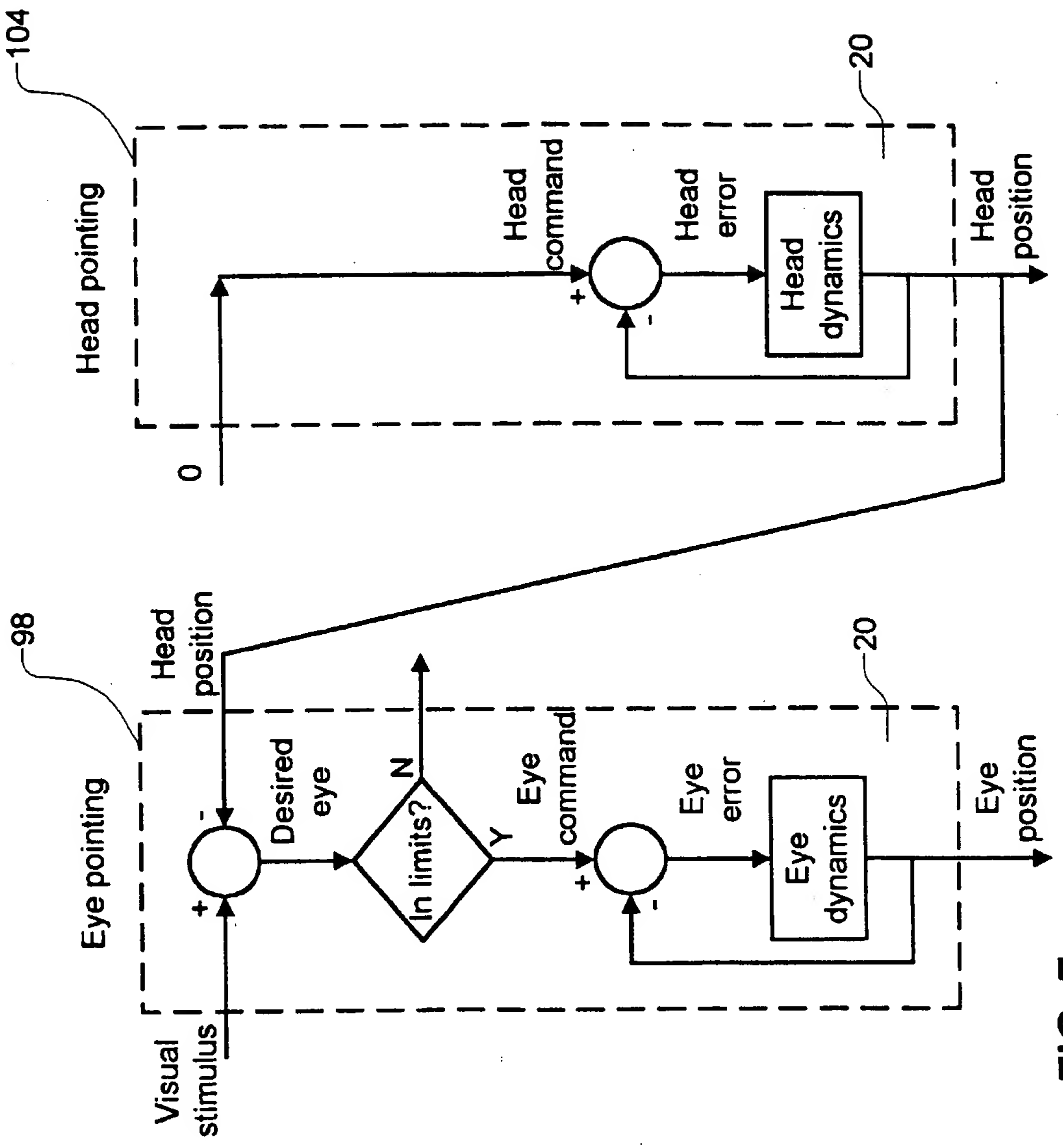
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FIG. 7

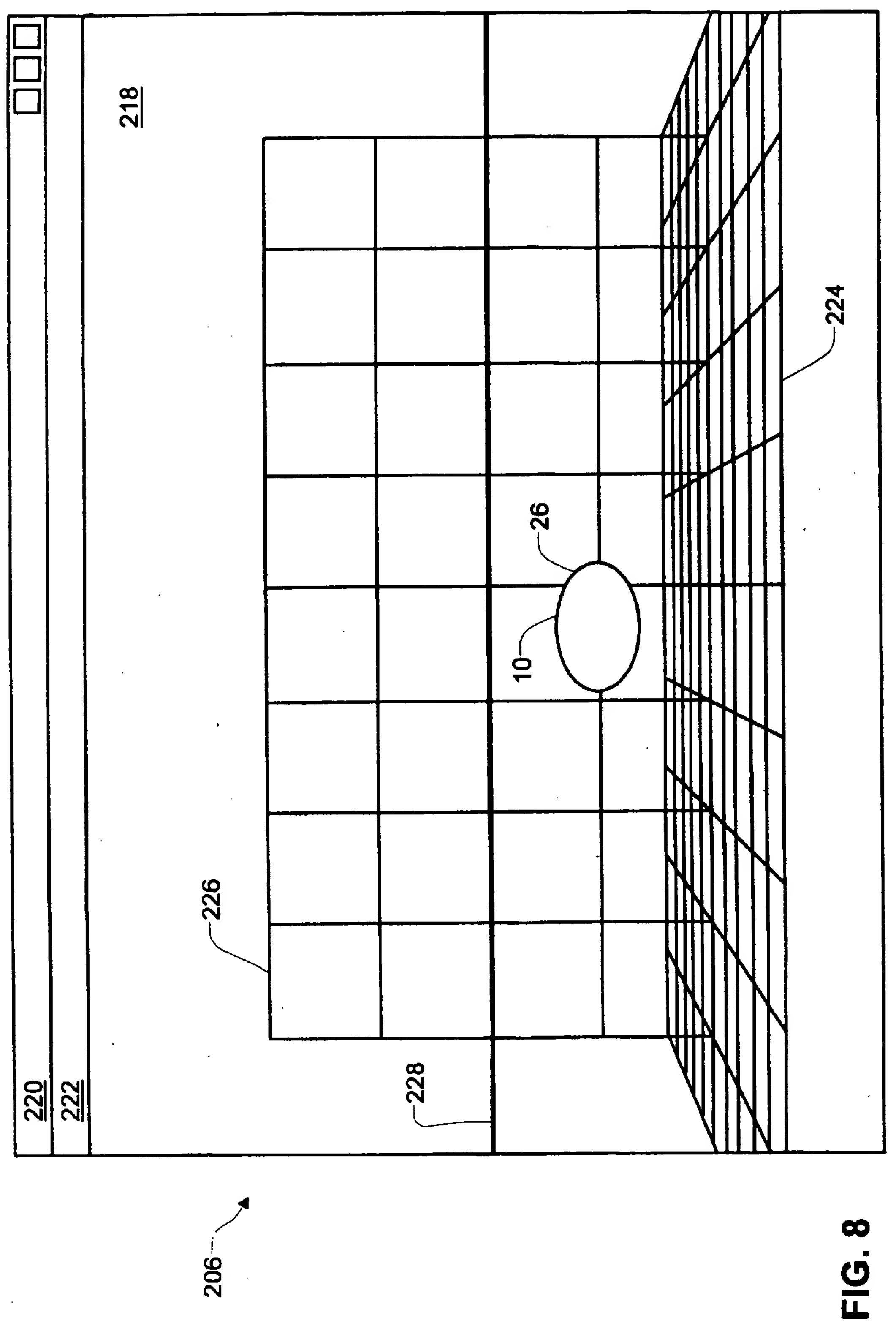
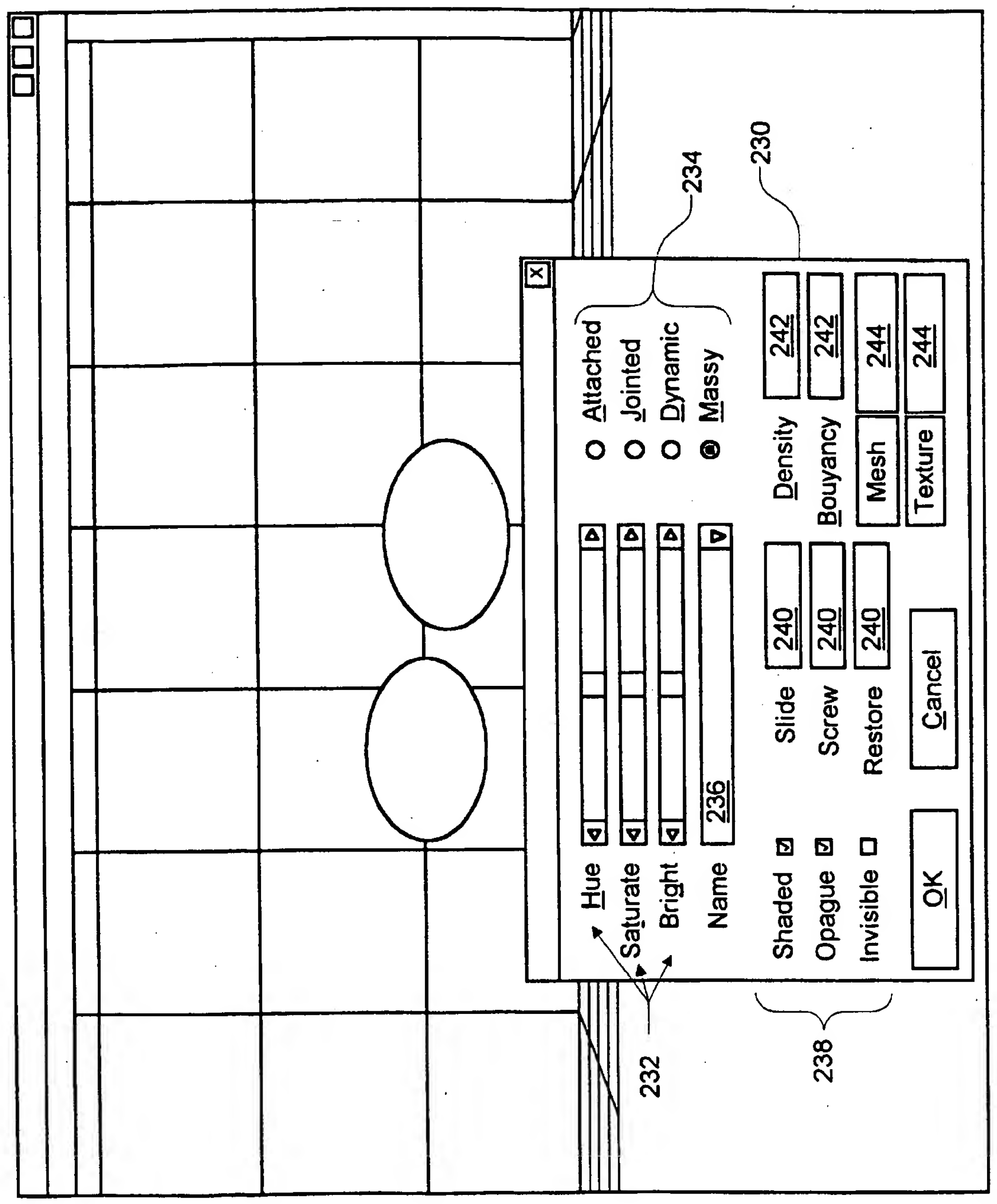


FIG. 8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Bright
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Jointed
Dynamic
Massy
Shaded
Opague
Invisible
Slide
Screw
Restore
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Density
Bouyancy
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Mesh
Texture
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234
238

FIG. 9

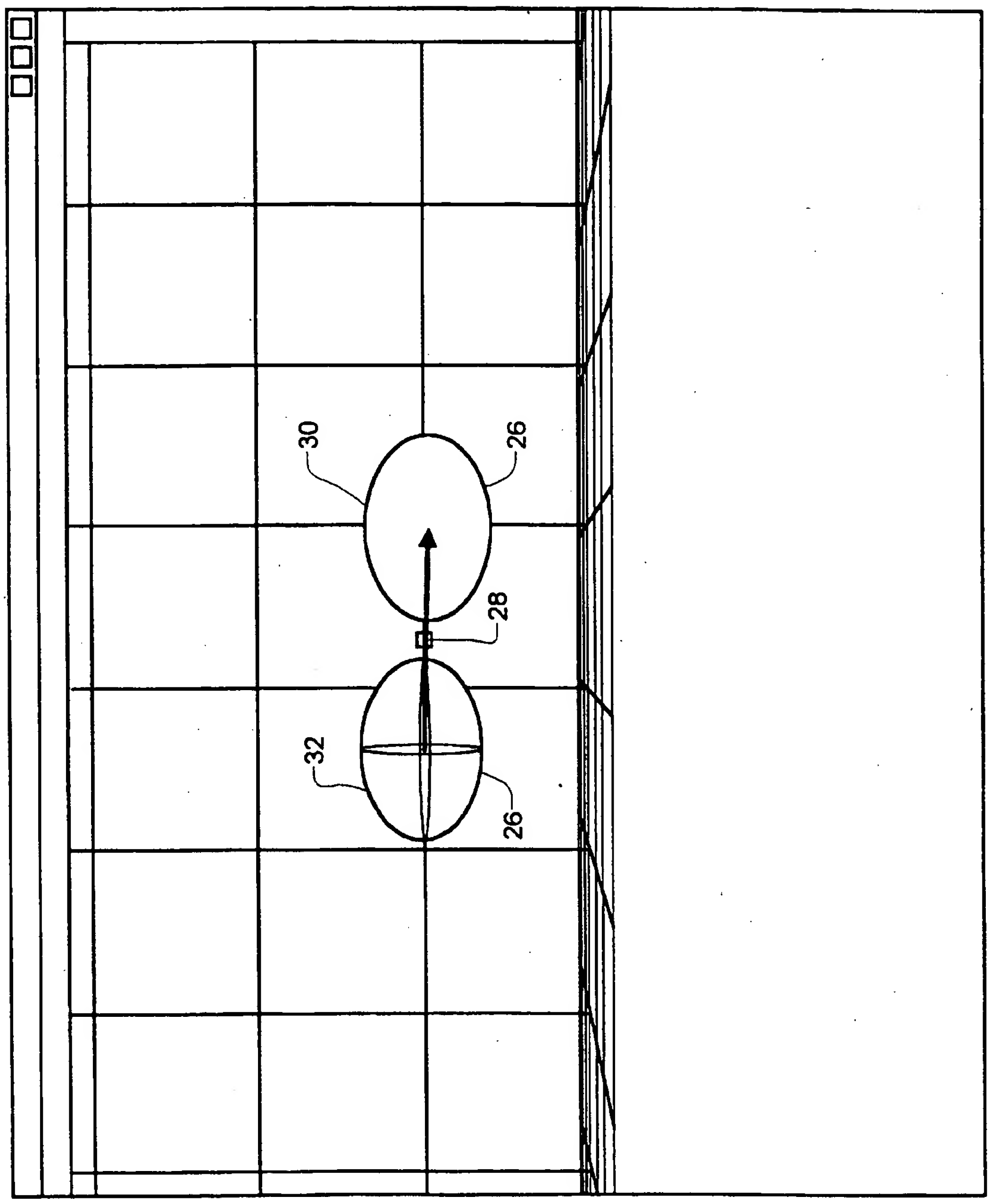


FIG. 10

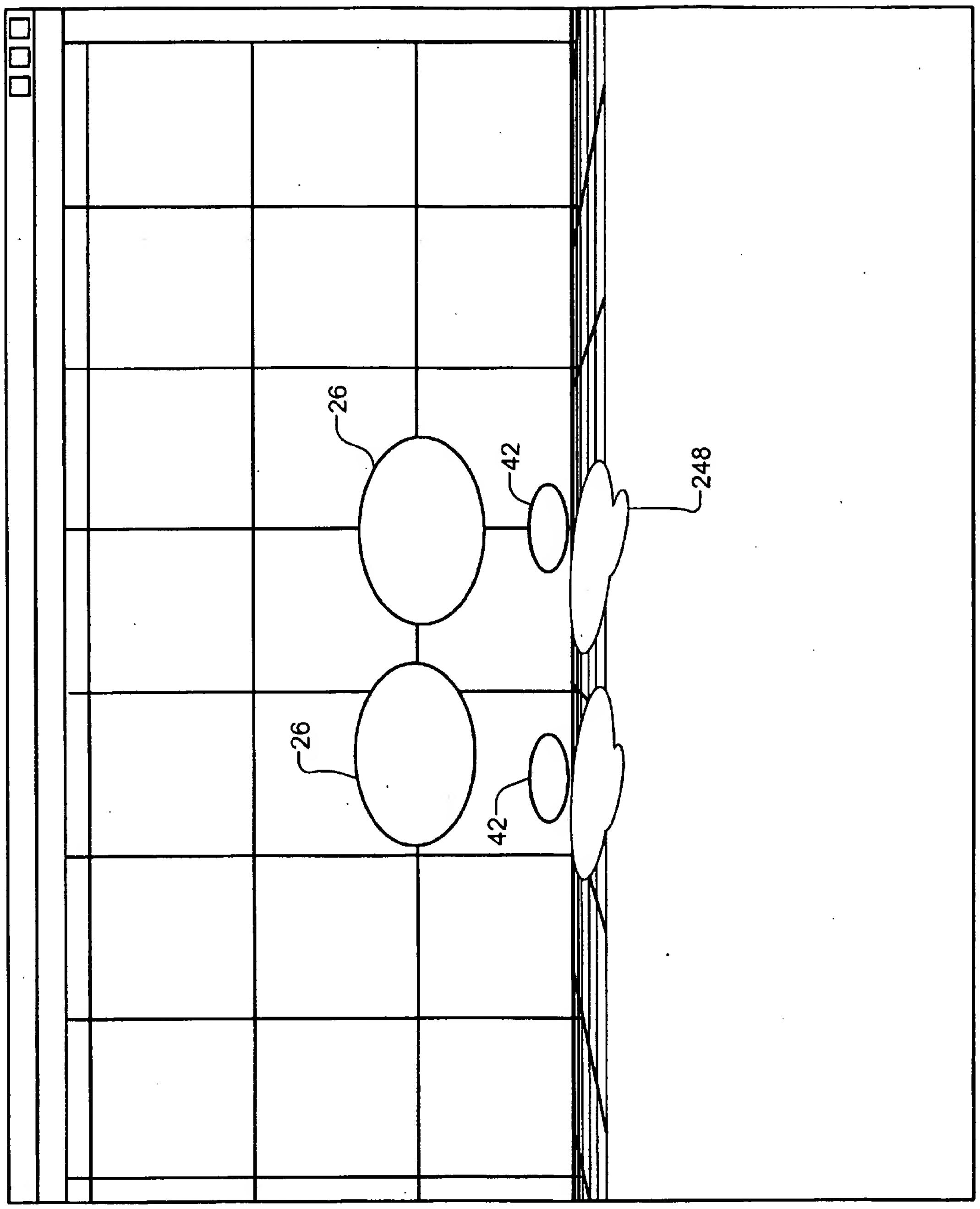


FIG. 11

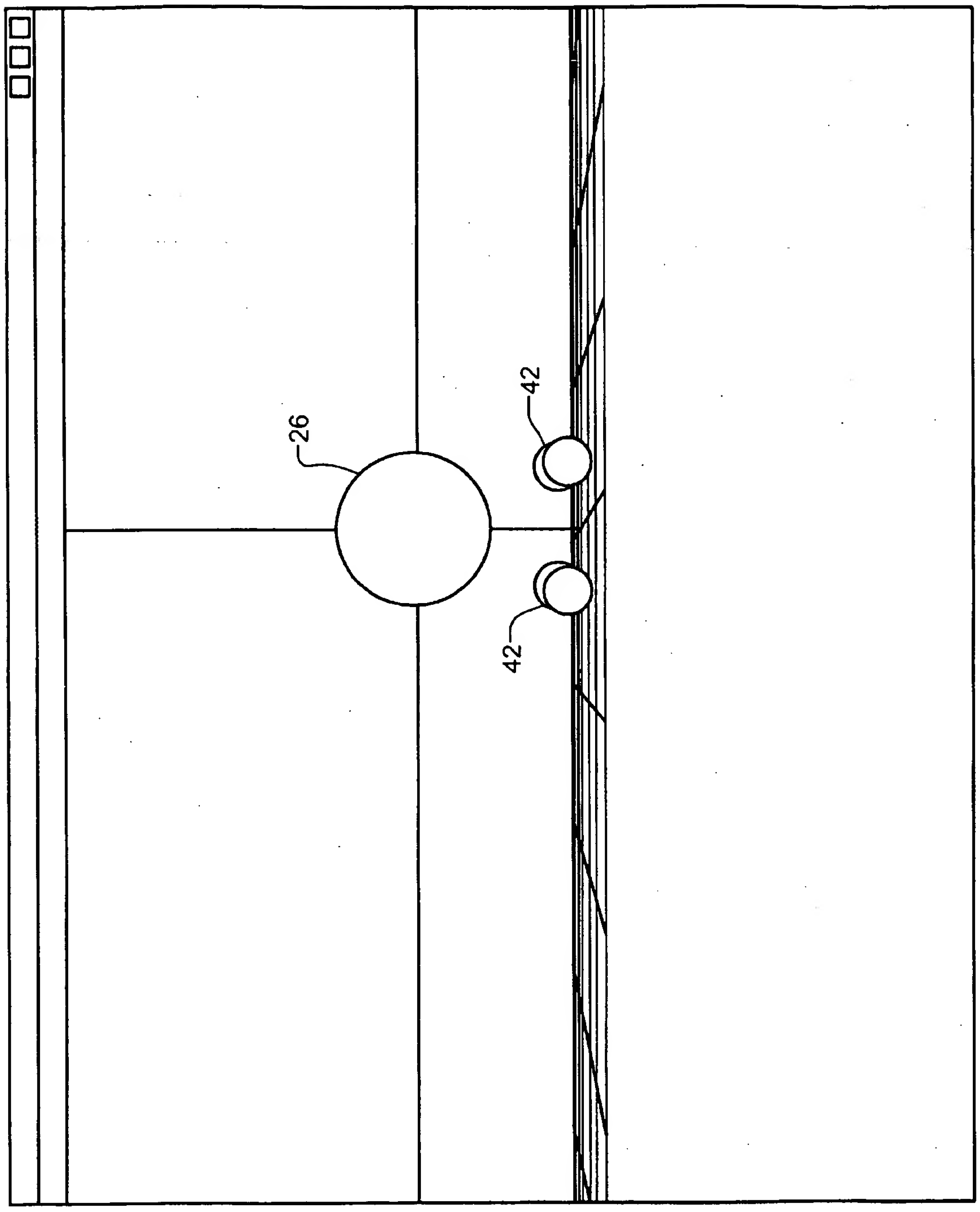


FIG. 12

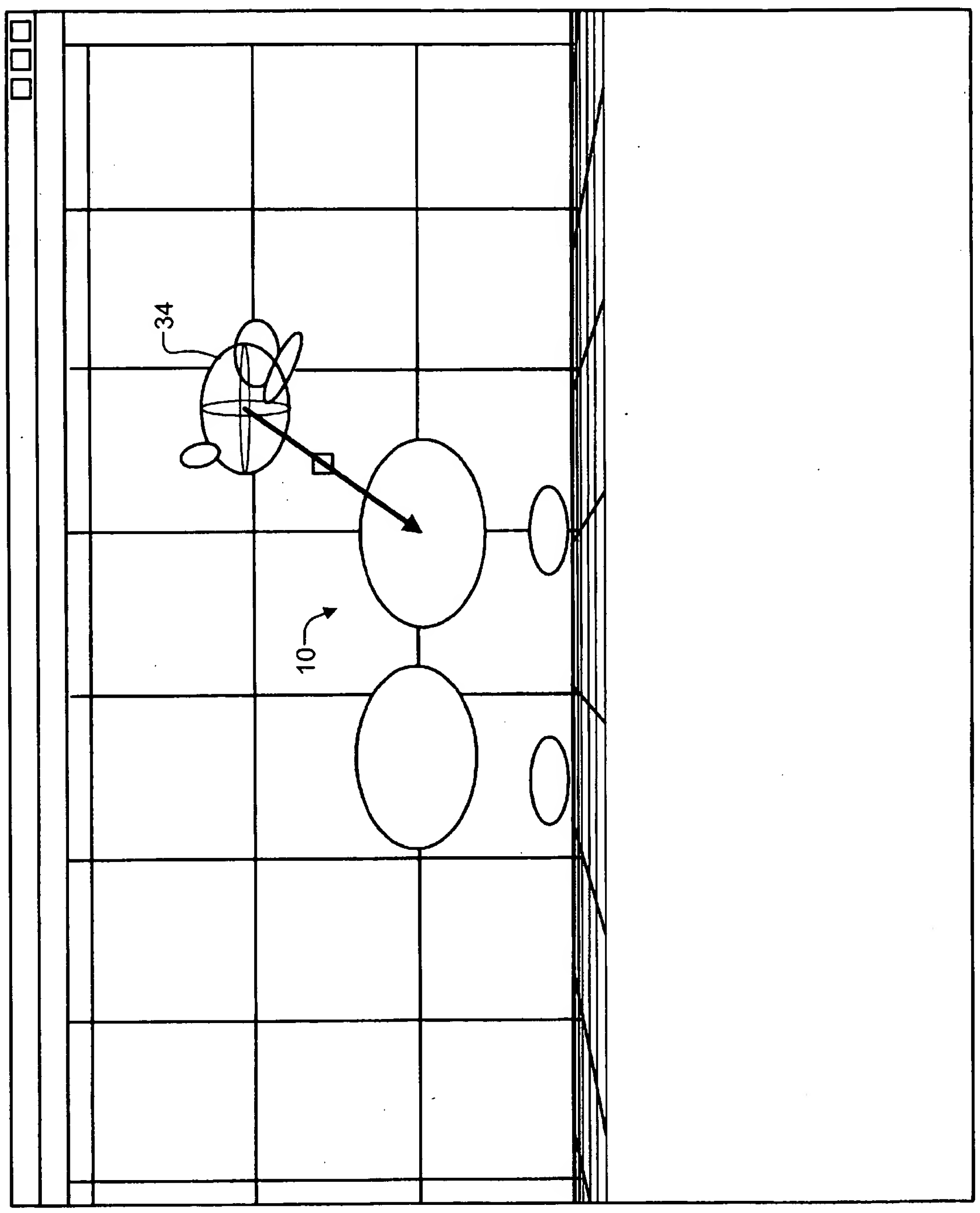


FIG. 13

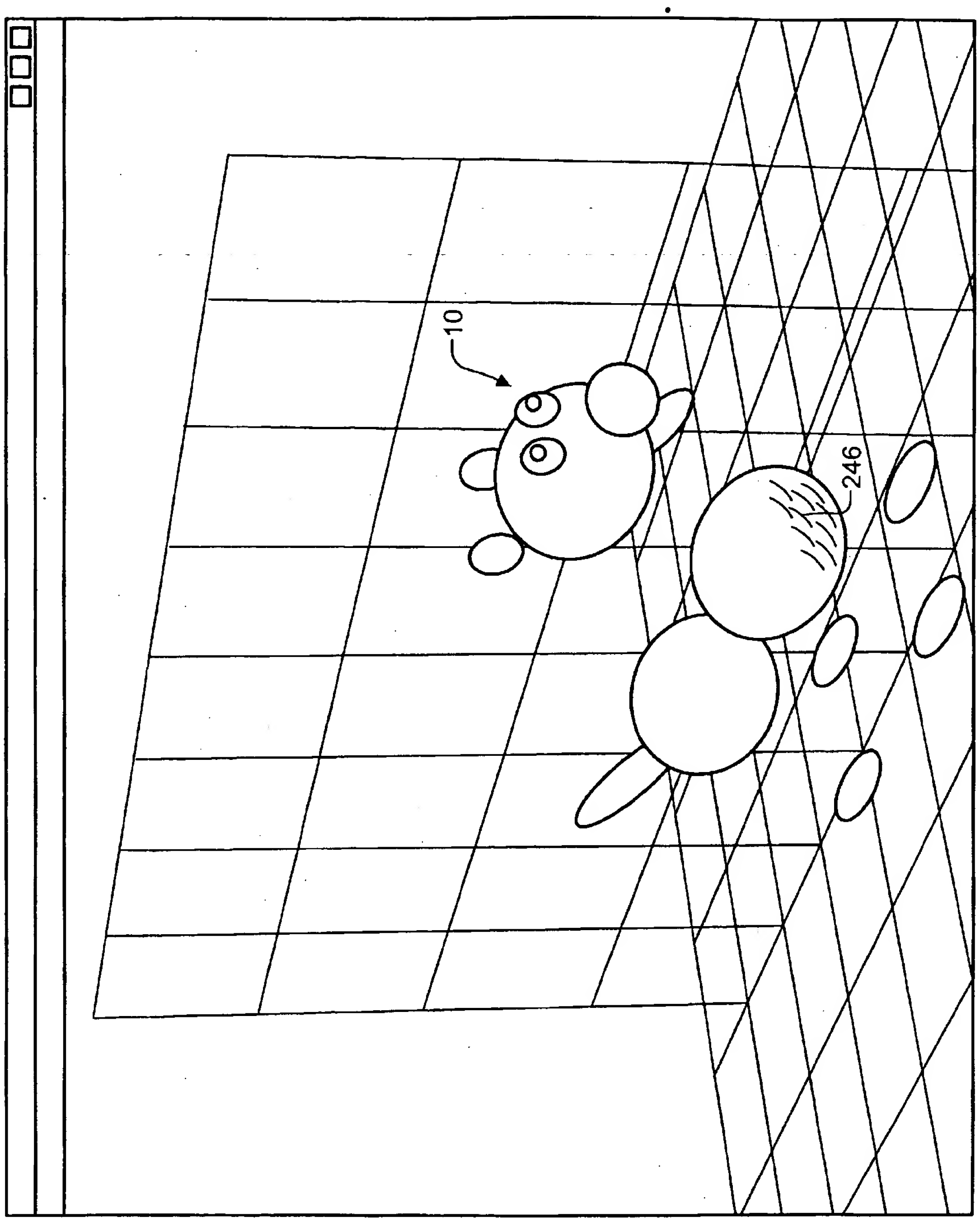


FIG. 14

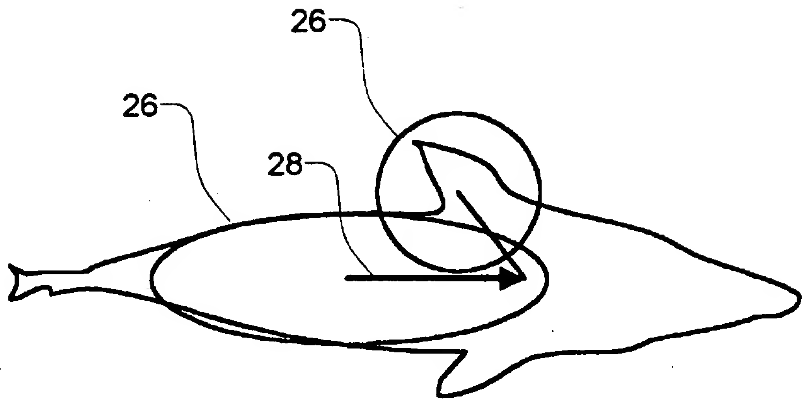


FIG. 15a

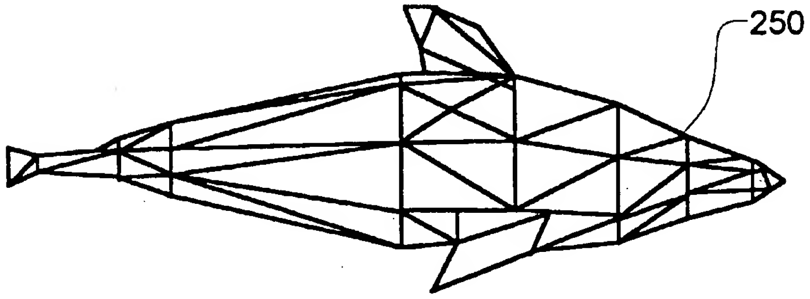


FIG. 15b

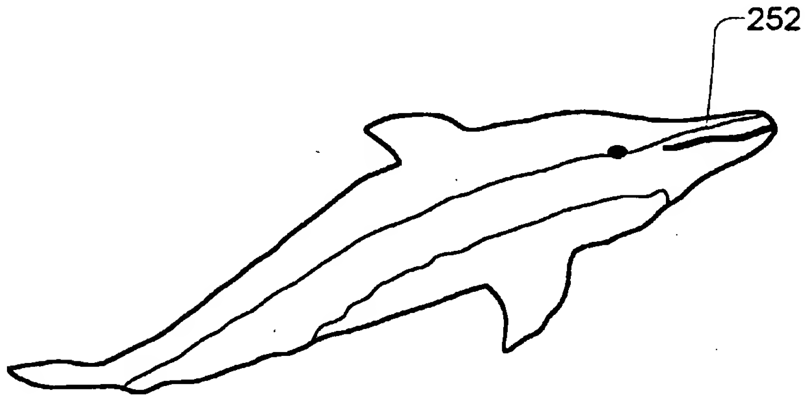


FIG. 15c

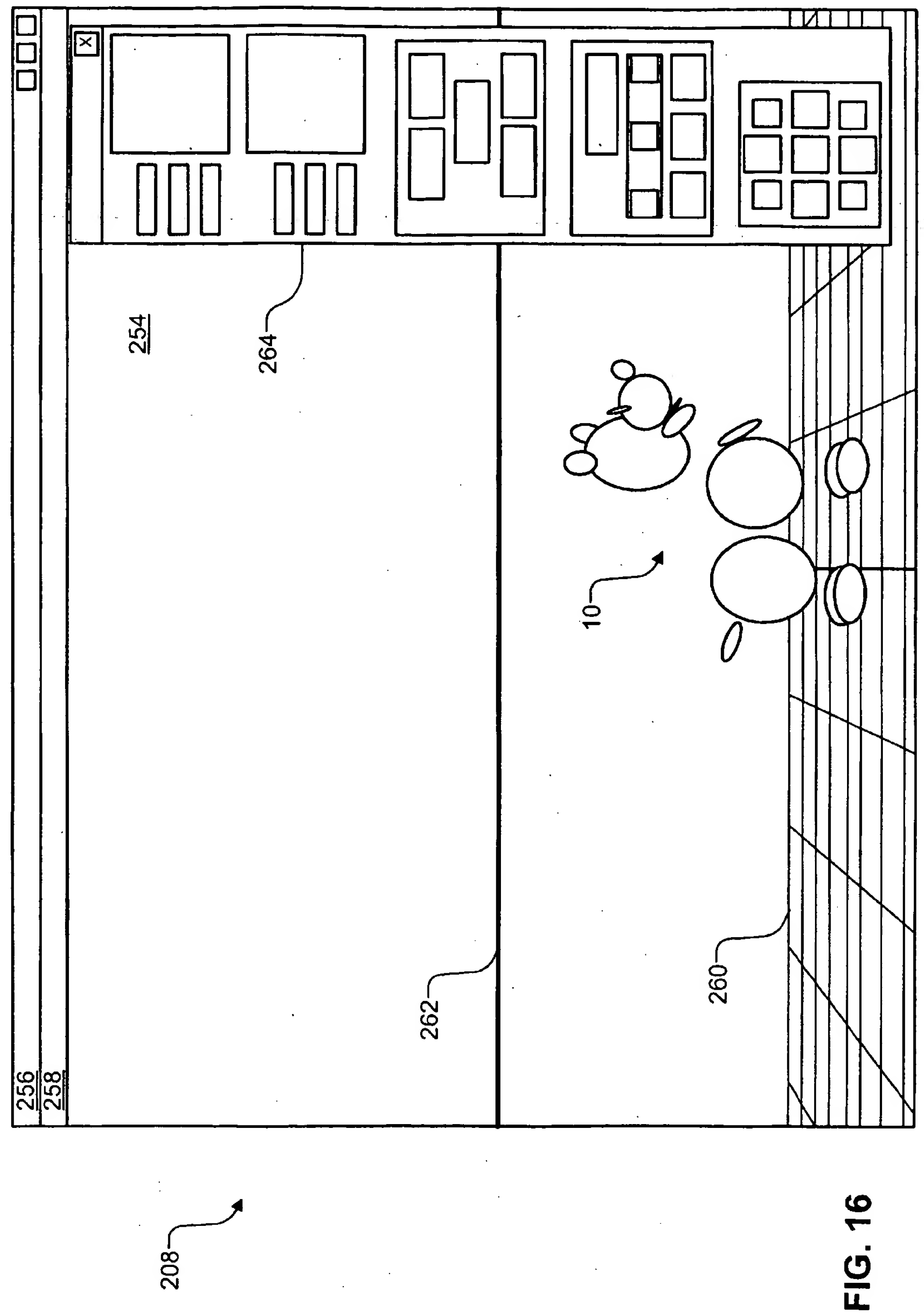
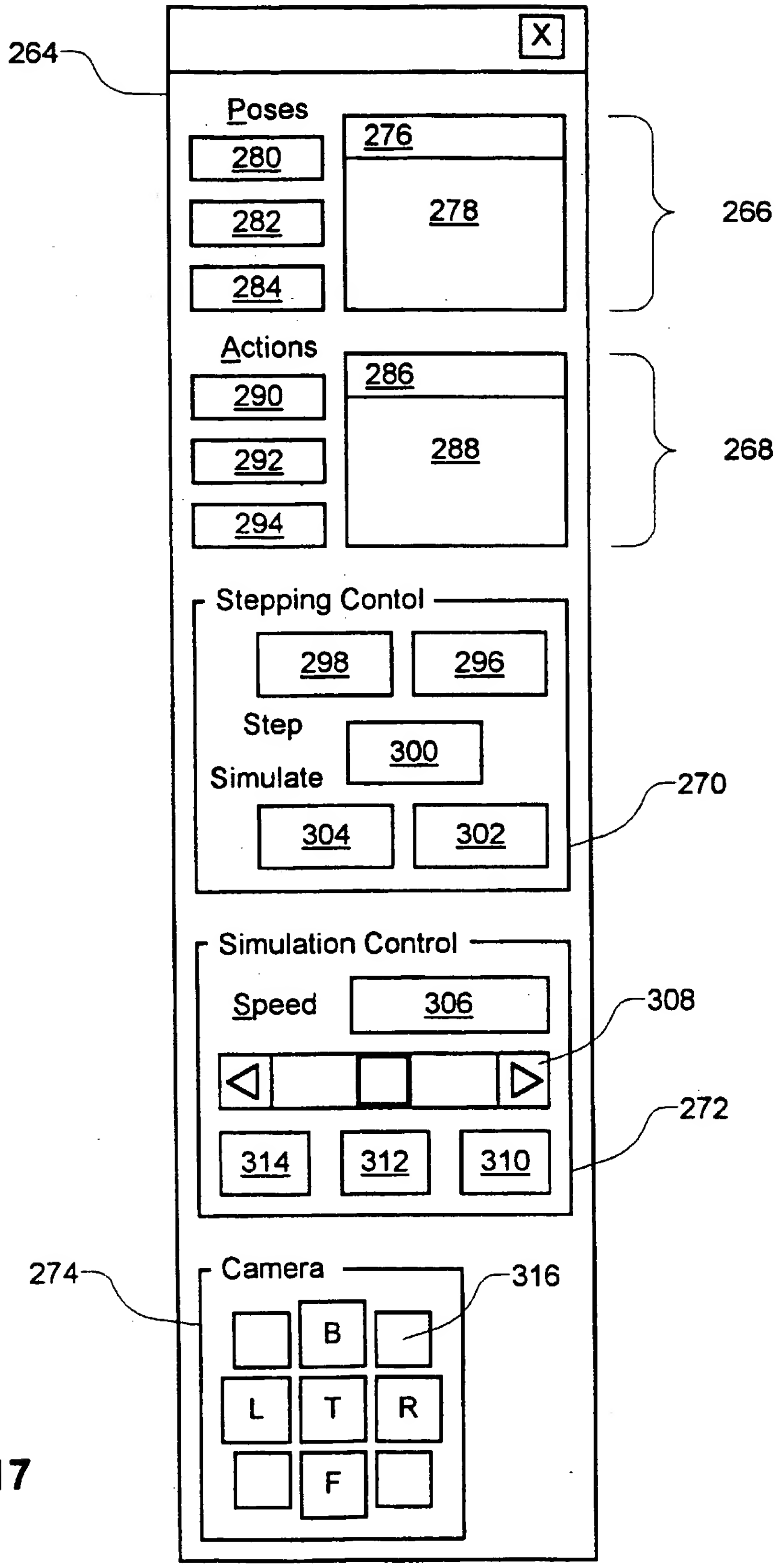


FIG. 16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Simulate
304
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Simulation Control
Speed
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312
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Camera
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B
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R
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FIG. 17

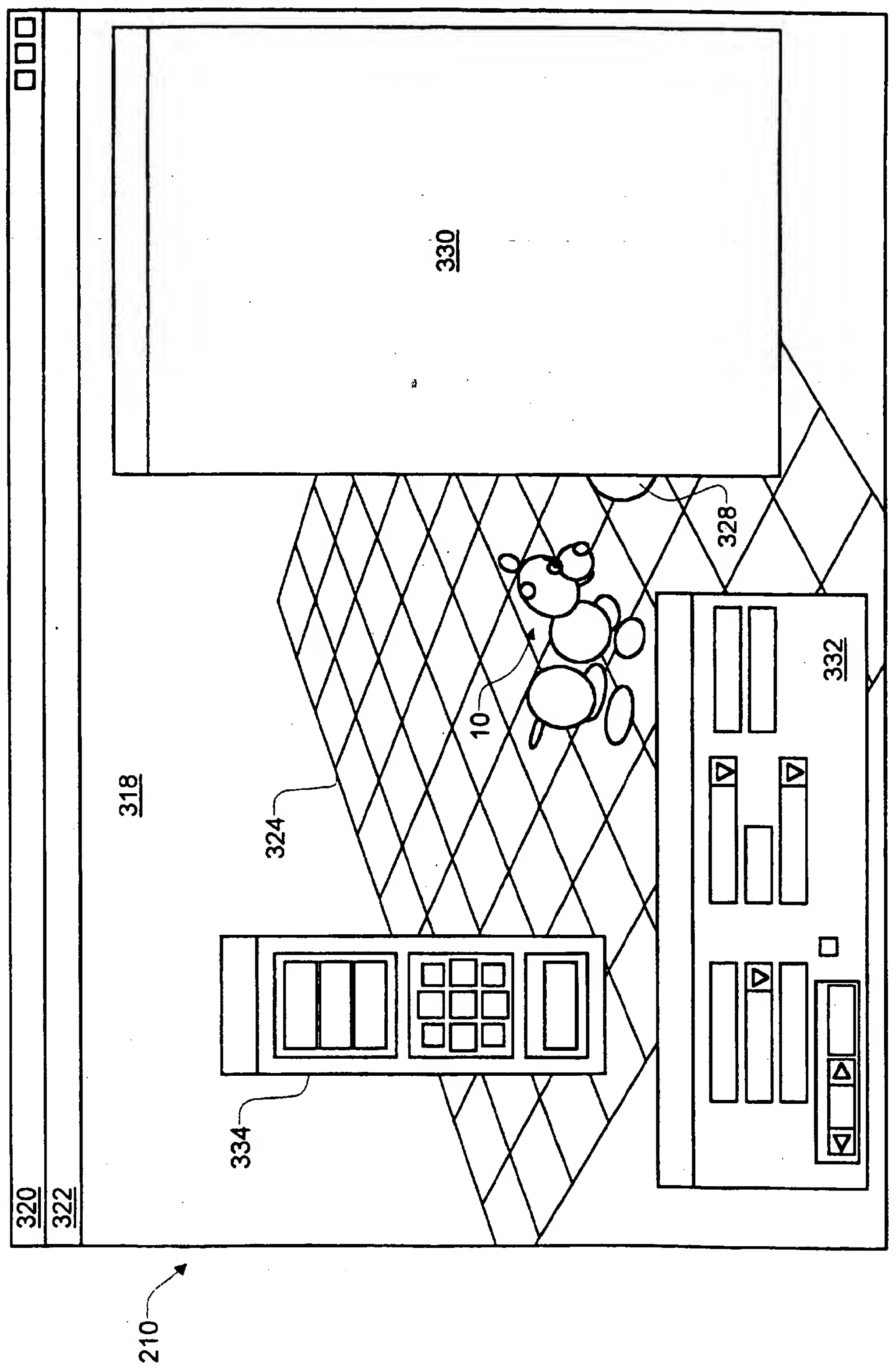
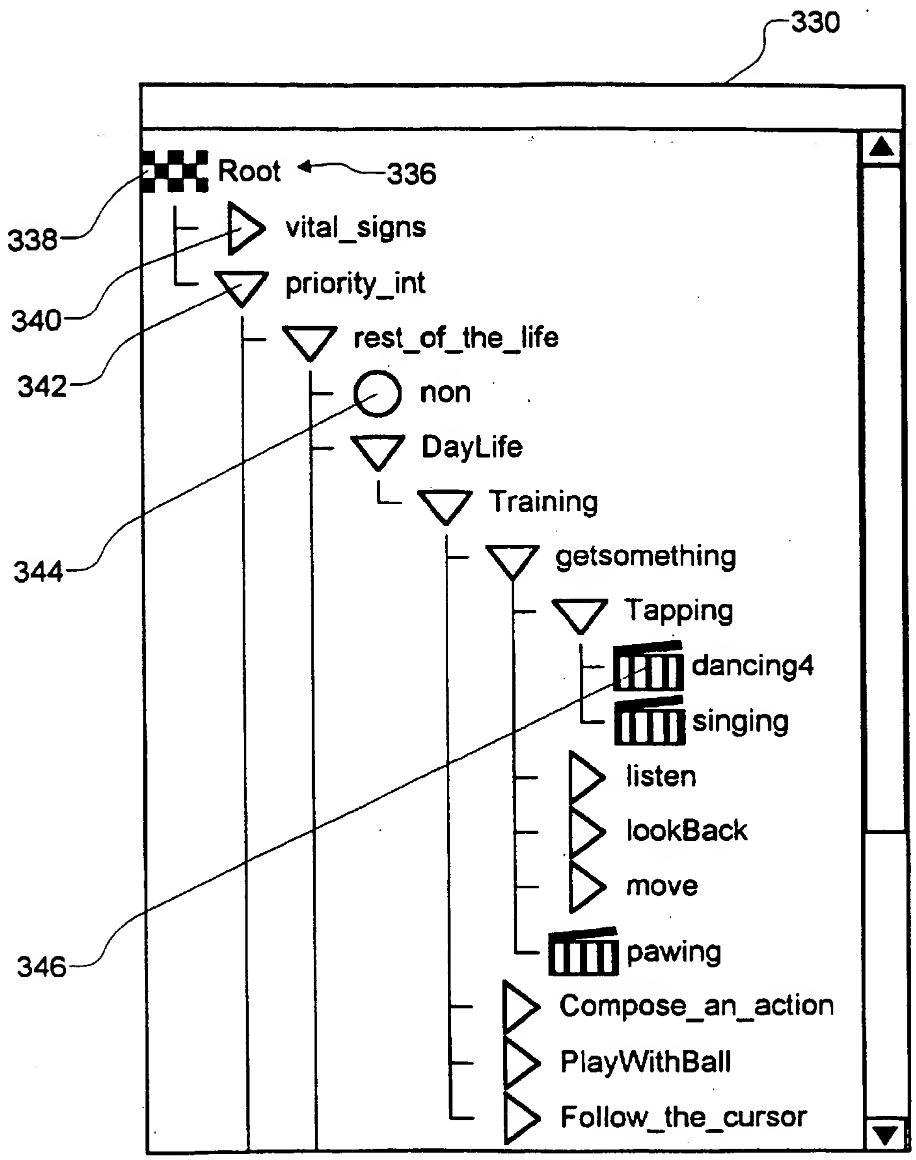


FIG. 18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pawing
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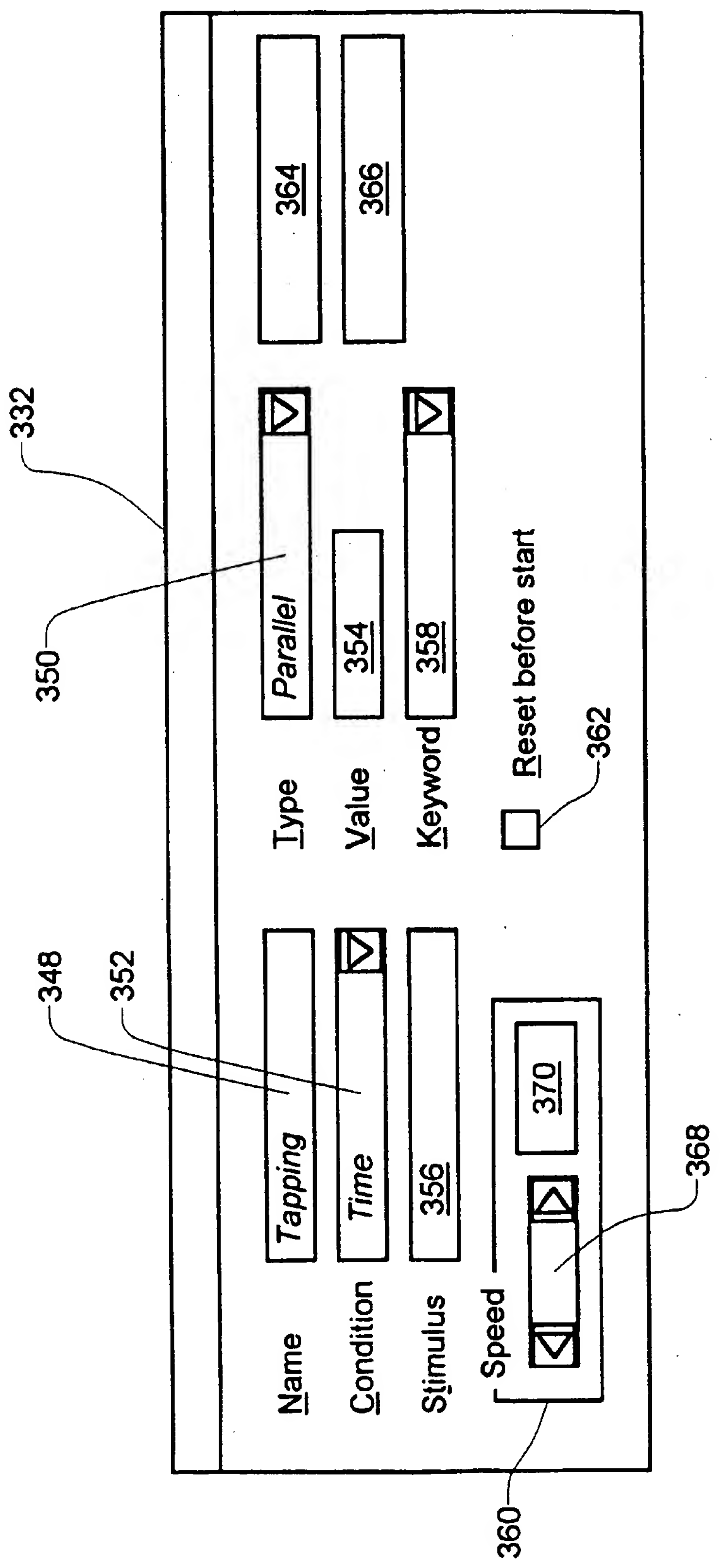
PlayWithBall
Follow_the_cursor

FIG. 19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362
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Condition
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Stimulus
356
Speed
370
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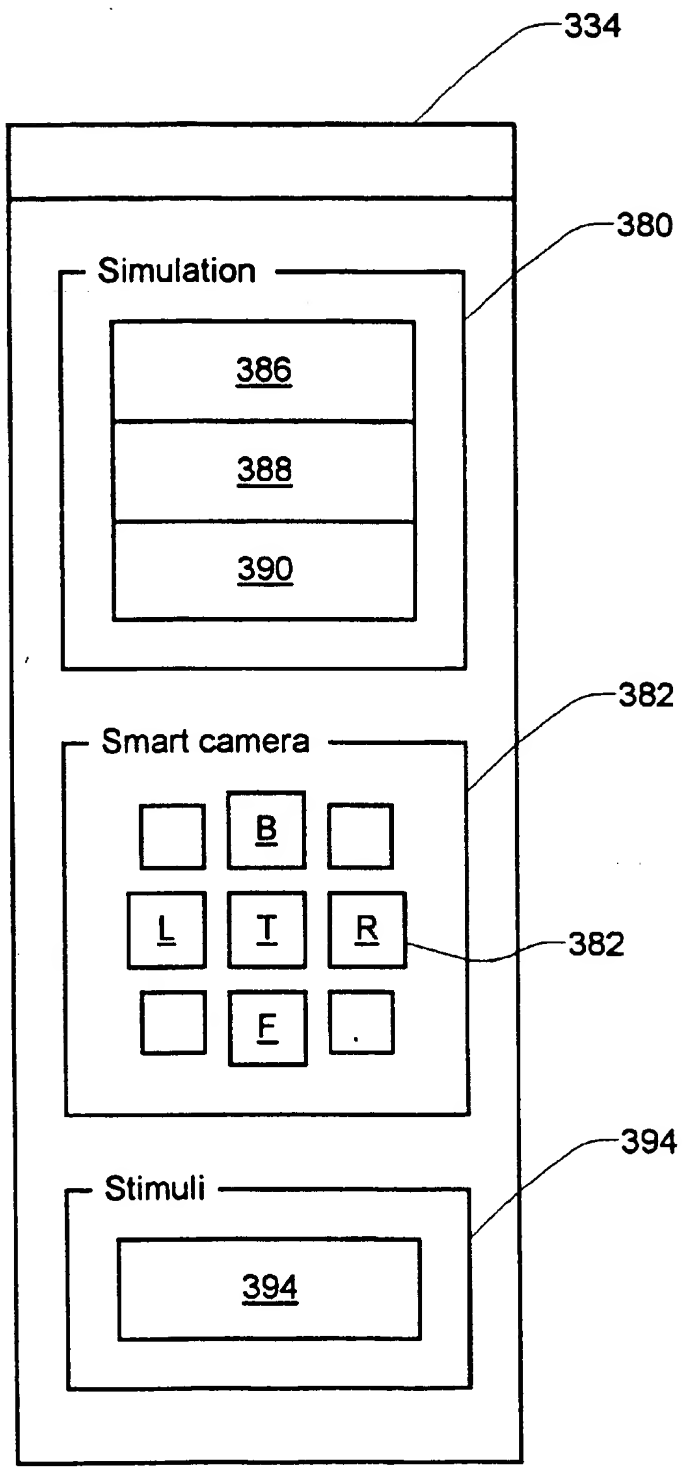
360

FIG. 20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Simulation
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388
390
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Smart camera
B
L
T
R
382
F
394
Stimuli
394

FIG. 21

CREATURE ANIMATION AND SIMULATION TECHNIQUE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of both U.S. Provisional Application No. 60/007,082, filed Oct. 13, 1995, titled "CREATURE ANIMATION AND SIMULATION TECHNIQUE," by inventors James B. ROSEBOROUGH and Timothy J. KOSTOLANSKY, and U.S. Provisional Application No. 60/025,056, filed Sep. 3, 1996, also titled "CREATURE ANIMATION AND SIMULATION TECHNIQUE," by inventors James B. ROSEBOROUGH, Timothy J. KOSTOLANSKY and Jaime R. del PALACIO.

TECHNICAL FIELD

The present invention relates generally to techniques used in simulating life-like characteristics in computer implemented simulations of bipeds, quadrupeds, and more complex creatures, as well as life-like motion of simple physical objects. It is the inventors anticipation that the invention will find primary application in the field of real-time computer generated graphics used for amusement. However, the invention also has potential application to more complex and non-real-time computer graphics fields, such as cartoon drafting, game scripting, advertising, event recreation, simulation of virtually any living organisms, and life-like motion of simpler physical objects.

BACKGROUND ART

Computer simulations of believable life-like behavior have been sought since virtually the first computer system was developed. Inherently users of computers have equated the logical abilities of computers to the ability to act in realistic "animalistic" manners, unfortunately often with disappointing results. Characteristics such as autonomous behavior, which is perceivable as personality, have been elusive to obtain, and when obtainable to any appreciable degree have required considerable human programming talent in traditional computer languages (which are notably difficult to learn, and inflexible and unforgiving to use). Such characteristics further have required considerable computer resources to implement and execute. Some succinct examples serves to illustrate this. How does one implement a simulated creature that has a behavior which is recognizable, and personally identified with by users, as "tired"? How does one implement a simulated creature so realistic that users forget that it is "virtual," and automatically attempt to speak to it?

Numerous attempts have been made to present users (i.e., viewers) with life-like simulations. Considerable work in this area (e.g., by Disney Studios and others), but all examples known to the inventors have used human animators. Some of these efforts have used sprite based animation, requiring ahead-of-time animation of set sequences, usually by human illustrators. Recently, largely in response to the phenomenal increases in computer system capabilities due to component price decreases, memory size increases, and processor power increases somewhat realistic simulations have begun to appear in the market, but these are still largely ahead-of-time animation of set sequences, stored in mass on voluminous media such as CD ROMs, comprehensively indexed for retrieval, and rapidly presentable on increasingly powerful computers so that users perceive them to be running in real-time (e.g., Doug Sharp of Microsoft Corporation's Advanced Authoring Tools Division pre-scripted interactive story titled "The King of Chicago," which uses hundreds of scenes of possible situations).

Notable exceptions to the above statements do exist, including the work of Massachusetts Institute of Technology's Media Lab such as Bruce Blumburg's "virtual dog," implemented on a system termed the Artificial Life Interactive Video Environment. However, considerable improvement over even this is eagerly sought by computer users, who desire true three-dimensional interactive simulations of lower animals, humans, and even life-like behaviors imparted to mere physical objects. Further, to coin a term, users seek "synthetic creatures" having improved representational simulation (as contrasted to the overwhelming prior art concentration on mere presentational simulation techniques). Still further, an eager body of authors seek tools with which to supply the noted demands of users, tools which provide reusability and portability of work product, yet which do not require the effort of learning traditional programming languages and techniques, and which eliminate the frustration and inefficiency generally experienced in dealing with the inflexibility and syntactical rigidity of traditional programming systems.

Finally, the term "virtual dog" has been used above, and it should be noted that the term "virtual pet" has come into (and perhaps already left) vogue. Bruce Blumburg's accomplishment is quite noteworthy, and other similarly noteworthy efforts exist (e.g., DOGZ by PF Magic of San Francisco, Calif.). However, to date, the inventors know of no simulation technologies which address what they perceive to be a first key obstacle to implementing and presenting simulated life-like behavior in real-time on commonly available computers, providing efficient usable tools to generate efficiently runable underlying physics, mechanical properties, and user perceivable properties (e.g., visual and audible properties) of synthetic creatures. Further, the inventors know of no simulation technologies, to date, which address what they perceive to be a second key obstacle in this field, providing a simple and efficient mechanism for defining and executing behaviors of such synthetic creatures.

DISCLOSURE OF INVENTION

Accordingly, it is an object of the present invention to provide simulations having improved life-like qualities.

Another object of the invention is to provide simulations which run efficiently on conventional computer systems.

Another object of the invention is to provide simulations which are are highly animated and have a truly interactive nature.

And, another object of the invention is to provide tools for authoring the improved simulations discussed above.

Briefly, one preferred embodiment of the present invention is a method of creating and simulating a synthetic creature on a computer system by authoring a character for the synthetic creature containing links and soft joints joining all but one such previously defined link, then authoring actions for the synthetic creature by positioning the character into a pose by moving the links into desired positions, and storing one or more such pose as an action. At this point the synthetic creature is sufficiently complete to be executed on a computer. Optionally, a behavior tree for the synthetic creature may be authored by defining behaviors which are grouped instances of actions and other previously defined behaviors, and recursively ordering the behaviors into the behavior tree in a hierarchical structure which is executable on the computer system.

An advantage of the present invention is that highly realistic and endearing life-like qualities are imparted to simulations using the invention.

Another advantage of the invention is that the simulations produced using the invention may be efficiently implemented on a wide range of available computer systems, including typical personal computers, workstations, and mainframe type computers.

Another advantage of the invention is that the simulations produced using the invention may be made highly interactive with other aspects of computer generated environments, and with users of computer systems.

Another advantage of the invention is that the simulations produced using the invention use a high level authoring of animated content, close to the human thinking process.

Another advantage of the invention is that the simulations produced using the invention is that it allows definition of animated works which are small and highly efficient encodings of animation.

And, another advantage of the invention is that it may be easily adapted to emerging computer technologies, such as the Internet, for online use of pre-authored implementations of the invention.

These and other objects and advantages of the present invention will become clear to those skilled in the art in view of the description of the best presently known mode of carrying out the invention and the industrial applicability of the preferred embodiments as described herein and as illustrated in the several figures of the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The purposes and advantages of the present invention will be apparent from the following detailed description in conjunction with the appended drawings in which:

FIG. **1** is a chart of layers and some of the elements used at respective layers when authoring the synthetic creatures of the present invention;

FIG. **2** is a depiction of a basic simulated animal, illustrating joint and link relationships;

FIG. **3** is a depiction of a simulated animal, illustrating major body parts and stylistically illustrating positive weight elements;

FIG. **4** is a depiction of the same simulated animal of FIG. **3**, stylistically illustrating positive and negative weight elements together;

FIG. **5** is a stylized time line and image frame depiction of an action of a synthetic creature;

FIG. **6** is a flow chart depiction of eye-pointing implemented as a set of independent and autonomous behaviors;

FIG. **7** is a flow chart depiction of graceful degradation, when one independent behavior is not fully implemented;

FIG. **8** is a screen capture of a typical character editor of the invention depicting starting of the creation of a synthetic creature;

FIG. **9** is a screen capture depicting how properties of a link in a synthetic creature may be tailored in a character editor controls window;

FIG. **10** is a screen capture depicting addition of link structure during continued authoring of the synthetic creature started in FIG. **8**;

FIG. **11** is a screen capture depicting initial definition of symmetric structure to the synthetic creature;

FIG. **12** is a screen capture depicting completion of the symmetric structure by mirrored copying of symmetric parts of the synthetic creature;

FIG. **13** is a screen capture depicting addition of additional major body links to the synthetic creature;

FIG. **14** is a screen capture depicting the structurally complete synthetic creature, now recognizable as a simulated dog and including the use of shading and shadow visual effects;

FIG. **15***a*, FIG. **15***b*, and FIG. **15***c* are screen captures a simulated dolphin, with FIG. **15***a* showing examples of some links emphasized in the dolphin as ellipsoids, with FIG. **15***b* showing the dolphin-like mesh structure emphasized in the dolphin, and with FIG. **15***c* showing the dolphin with a "skin" texture added;

FIG. **16** is a screen capture of a typical animal editor of the present invention in use;

FIG. **17** is an expanded view of a key part of FIG. **16**;

FIG. **18** is a screen capture of a typical behavior editor of the present invention in use; and

FIG. **19**, FIG. **20** and FIG. **21** are expanded views of key controls windows in FIG. **18**.

BEST MODES FOR CARRYING OUT THE INVENTION

The preferred embodiments of the present invention are simulated creatures, and a group of simulation authoring tools for creating and enhancing various aspects of such creatures. Specifically, the members of the group of simulation authoring tools include a universe editor, a character editor, an action editor, a behavior editor, and an environment editor. Further, not all of the authoring tools are necessarily distinct, or necessarily needed for all implementations of synthetic creatures.

The initial goal of development which lead to the present invention was creation of simulated creatures, specifically "virtual pets" which run in computer generated environments and optionally interacted with users of the host computer system. The inventors have since further refined the invention and extended its capabilities to include simulating non-pet-like animals, simulating characterized humans, and simulating characteristics of life in inanimate objects. Over time the products of the present invention have been termed simulations, virtual pets, and most recently synthetic creatures. Herein the term synthetic creature will be used, and will be referred to by the general reference character **10**.

DEFINING LIFE IN A SYNTHETIC CREATURE:

The inventors have modeled their synthetic creatures **10** using a system with a number of distinguishable layers **12** (FIG. **1**). In the preferred embodiment these layers **12** include the universe **14** where the synthetic creature **10** "lives," the character **16** (basic physical characteristics; e.g., cat vs. dog, long limbs vs. short, etc.) which the synthetic creature **10** will have, the actions **18** which the synthetic creature **10** will be capable of, the behaviors **20** which the synthetic creature **10** will exhibit, and the environment **22** in which the synthetic creature **10** will perform. By dealing with these layers **12** separately the inventors have been able to abstract out much simulation complexity. Another key benefit of the use of layers **12** is that the invention may be more easily implemented so that authors (a term herein used to refer to those who create synthetic creatures **10**) and users (herein used to refer to those who ultimately use already authored synthetic creatures **10**) do not need any programming experience per se, since simple "applications program" type interfaces may be used for authoring the layers **12**, and no "code" in a traditional computer language need be used by either the authors or users. (Although considerable power can be added to the layers **12** by adding special modules, which may use more traditional computer code methodologies, if desired.) This approach leads to the synthetic creatures **10** which are very quickly and easily changed and enhanced. Further, this approach makes possible considerable work reusability and portability of work for synthetic creatures **10**, on all of the layers **12**. For example, attributes of a dog synthetic creature **10** may be easily reused (even put in libraries, and distributed as such to other authors) to create other dog synthetic creatures **10**, and physical attributes of a dog synthetic creature **10** may be combined with behavioral attributes of a cat synthetic creature **10**, to create unusual results. Still further, the use of distinct layers **12** permits abstracting out much authoring complexity.

The layers **12** may be distinguishable, but it is not absolutely necessary that this always be done. For example, the universe **14** and the character **16** are two layers **12** which the inventors presently do not make highly distinct. To date, the inventors have simply incorporated the universe **14** into embodiments of the character **16**. However, there is no reason why the universe **14** can not be implemented as a truly separate layer **12**, and it is envisioned that capabilities of the synthetic creatures **10** would be expanded in useful manner if this were done, say to use as a teaching aid for physical mechanics, or to try out non-Newtonian rules of physics.

The Universe of a Synthetic Creature:

For a synthetic creature **10** to appear realistic the universe **14** in which it lives should be constant, i.e., it should impose the same rules of physics on a synthetic creature **10** as it does on other objects in that universe **14**. For example, a synthetic creature **10** and a ball which it is playing with should both obey the same rules, say of Newtonian physics. This requires that the universe **14** specify in some manner an underlying physics **24**.

As noted, above, the inventors integrate the universe **14** into the character **16** in present implementations. This relieves authors of the need to separately concern themselves with the universe **14**, when an earth-normal type universe **14** is used.

Conceptually the universe **14** is the lowest layer **12**. However, unlike higher layers **12** which have little meaning without lower layers **12** (e.g., behaviors **20** can not be authored without existing actions **18** to work with, and while actions **18** can not be authored without an existing character **16** to work with) the pre-existence of a universe **14** is not always necessary for authoring of the higher layers **12**. However, not placing the universe **14** at the lowest layer **12** can lead to problems. The classic squared-cubed problem of mechanics is one example (this support structure vs. mass problem is the reason why weighty creatures must look like elephants or hippos, with thick legs, and why very light creatures can have very thin legs, like ants and spiders). If "realities" of a universe **14** are not imposed upon the character **16** of a synthetic creature **10** early, considerable work on actions **18** and behaviors **20** may be adversely effected.

The Character of a Synthetic Creature:

FIG. 2 depicts a very basic generic synthetic creature **10**. The joints and limb segments of the synthetic creature **10** there are shown as loosely connected interacting independent links **26** (depicted by ovals, or more correctly ellipsoids, since the character **16** is a three-dimensional representation) and joints **28** (depicted by arrowed lines with the arrow end pointing at a higher level link **26**) that

implement the physics of everyday life (i.e., they function subject to the rules of the universe **14**). The links **26** represent rigid physical objects, while the joints **28** are manifested as an interaction between two specific links **26**. This provides a very soft fluid feeling to the synthetic creature **10**, not present in other work to date.

Conceptually, characters **16** are hierarchical, starting with a non-associated link **30** at the highest level, and having depending child links **32** at lower levels in the hierarchy. Child links **32** are links **26** which have an associated joint **28** connecting them to higher ordered links **26**, until the non-associated link **30** is reached. Links **26** receive interaction forces and torque from each of the joints **28** lower in the hierarchy (although this may be extensively controlled by specifying various types of joints **28** which interact in special manners).

FIG. 3 illustrates a number of recognizable body parts for a typical synthetic creature **10**, which will be referred to often herein. These include a head link **34** (with features such as eye links **36**), a chest link **38**, a lower body link **40**, foot links **42**, and a tail link **44**.

FIG. 3 and FIG. 4 also illustrate how a synthetic creature **10** is able to right itself, and otherwise control itself in an environment **22**. The components of weight and mass are shown split out for each link **26** and treated separately, so that the overall behavior of a synthetic creature **10** closely mimics the closed-loop controlled behavior of a real animal, endowing the synthetic creature **10** with additional lifelike qualities. Weight is depicted by downward pointing arrows for positive weight **46** and upward pointing arrows for negative weight **48**. Mass, which is never negative, is not represented by any element in the figures, since its presence is implied.

Soft Joints:

Part of simulating an animal requires simulating the dynamic characteristics of its links **26** (i.e., its limb segments) and the joints **28** connecting them. The classical approach to this problem has been to put infinitely stiff joints, in the form of mathematical constraints, between links representing each limb segment, and then solve the complete mathematics of the system at each time step. Unfortunately, the number of computations in this approach increases as the cube of the number of links, or becomes intractable due to the need to invert a complex non-linear functional relationship (the "inverse kinematics" problem), since the whole system of characteristic equations of motion must be formulated completely beforehand. Further, overall, this approach produces motion that is stiff, mechanical, and robotic. However, this traditional approach is widespread because most animals have relatively stiff joints in some dimensions, and flexibility in other dimensions, and it therefore initially seems appropriate to introduce the stiffness as a set of mathematical constraints. This approach is also common in the robotics field, where devices are built to be stiff in linear and angular degrees of freedom.

In contrast to the traditional approach, the inventors formulate each link **26** independently of the others, so that the number of computations at each time step is proportional to the number of links **26** rather than the cube of that number. The inventors have termed this concept "soft joints," since it is a way of simulating a combination of joints **28** and links **26** (i.e., limb segments) in a synthetic creature **10** that results in a very fluid, soft, and natural appearance. Since each link **26** behaves independently, its equations of motion need be implemented only once. In this manner a meaningful approximation to a true massy six-degree-of-freedom model becomes feasible, and imparts an additional realism to the synthetic creature **10**.

The inventors' approach further uses calculation of joint **28** interaction forces at each time step. These may be directly computed from the interacting joint **28** states by using state velocities. However, it should be appreciated that conventional control rules may be used quite straightforwardly for this portion of the inventive approach. A variety of joint **28** types for handling varying levels of interaction forces may be implemented, to address a range of needs varying in complexity and computational burden, thus permitting simpler joint **28** types to be applied where sufficient.

Yet another key aspect of the inventors' approach is association of each joint **28** with a child link **32** in a hierarchical arrangement terminating with one non-associated link **30** not having a joint **28** associated with it. This provides a notational convenience, with the advantage that there is no longer any problem defining a base link, nor is there any need to explicitly compute the group center-of-mass or perform other unwieldy calculations during a simulation of a synthetic creature **10**. Using ordinary object-oriented programming techniques, specialized links **26** can be formed which are massless or which have other special properties, thereby simplifying computation without introducing instabilities.

Equations used by the inventors to perform the above calculations for mass properties of connected rigid links are presented below:

Change of coordinates for velocity and force terms in a rigid link:

Impart acceleration $\dot{v}_0$ and rotational acceleration $\dot{\omega}_0$ on an object rotating at ω The kinematic constraint means that at point a in the object, the local acceleration $\dot{\omega}_a$ and angular acceleration $\dot{\omega}_a$ are,

$$\dot{v}_a=\dot{v}_0+\dot{\omega}_0\times a+\omega\times(\omega\times a);\ \dot{\omega}_a=\dot{\omega}_0$$

By defining a matrix,

$$R(a)=\begin{bmatrix} 0 & -a_z & a_y \\ a_z & 0 & -a_x \\ -a_y & a_x & 0 \end{bmatrix}$$

which has the properties,

$$R(-a)=-R(a)=R^T(a)$$

we can express cross products as matrix products through the following identities, i.e.

$$a\times b=R(a)b=R^T(b)a=-R(b)a=R(-b)a=-b\times a$$

This allows us to use column vectors for all quantities, including expressions involving cross products. The acceleration equations can then be written,

$$\begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix}=\begin{bmatrix} 1 & R^T(a) \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}+\begin{bmatrix} \omega\times(\omega\times a) \\ 0 \end{bmatrix}$$

which can be inverted to provide the reverse transformation

$$\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}=\begin{bmatrix} 1 & R(a) \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix}+\begin{bmatrix} \omega\times(\omega\times -a) \\ 0 \end{bmatrix}$$

A force F_a and torque T_a acting at a is equivalent to a force F_0 and torque T_0 acting at the center of gravity according to

$$F_0=F_a;\ T_0=T_a+a\times F_a$$

so that the following transformation of coordinates can be used regarding force and torque

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}\begin{bmatrix} F_a \\ T_a \end{bmatrix};\ \begin{bmatrix} F_a \\ T_a \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ R^T(a) & 1 \end{bmatrix}\begin{bmatrix} F_0 \\ T_0 \end{bmatrix}.$$

Reaction forces at a joint and their effects on the body dynamics:

Suppose at joint a there is an external mass attached which has reaction forces as a function of the local linear and rotational acceleration expressed in local body coordinates conforming to the equation,

$$\begin{bmatrix} F_a \\ T_a \end{bmatrix}=[M_a]\begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix}+\begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix}$$

We first recognize the fundamental force and torque balance that must occur, expressed at the body center,

$$\epsilon F=m_0\dot{v}_0$$

and

$$\epsilon T=I_0\dot{\omega}_0$$

then expand all terms and convert all coordinates to local body centered coordinates according to the transformations above, and solve for the force and torque that must act on the body center as a function of the body centered linear and rotation accelerations, as follows

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix}=\begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix}\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}+\begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}\begin{bmatrix} F_a \\ T_a \end{bmatrix}$$

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix}=\begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix}\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}+\begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}[M_a]\begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix}+ \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}\begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix}$$

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix}=\begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix}\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}+\begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}[M_a]+\begin{bmatrix} 1 & R(a) \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}+ \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}[M_a]\begin{bmatrix} \omega\times(\omega\times a) \\ 0 \end{bmatrix}+\begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix}\begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix}$$

Combining terms yields the force-acceleration relationship at the body center

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix} = \left(\begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_a] \begin{bmatrix} 1 & R^T(a) \\ 0 & 1 \end{bmatrix} \right) \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \left([M_a] \begin{bmatrix} \omega \times (\omega \times a) \\ 0 \end{bmatrix} + \begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix} \right)$$

Generalizing, we can say the effective mass-torque relations at the object center are governed by,

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix} = [M_0] \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

where

$$[M_0] = \begin{bmatrix} m_0 & 0 \\ 0 & I_0 \end{bmatrix} + \sum_i \begin{bmatrix} 1 & 0 \\ R(a_i) & 1 \end{bmatrix} [M_{a_i}] \begin{bmatrix} 1 & R^T(a_i) \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix} = \sum_i \begin{bmatrix} 1 & 0 \\ R(a_i) & 1 \end{bmatrix} \left([M_{a_i}] \begin{bmatrix} \omega \times (\omega \times a_i) \\ 0 \end{bmatrix} + \begin{bmatrix} f_{0a_i} \\ t_{0a_i} \end{bmatrix} \right)$$

Change of coordinates for basic mass parameters:

The frame in which the mass parameters are computed can be converted to a different body frame by substituting the change of coordinates already provided, so that if the mass parameters are known at one point in the rigid body, they can be computed for another point as follows:

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix} = [M_0] \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 \\ R^T(a) & 1 \end{bmatrix} \begin{bmatrix} F_a \\ T_a \end{bmatrix} = [M_0] \left(\begin{bmatrix} 1 & R(a) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix} + \begin{bmatrix} \omega \times (\omega \times -a) \\ 0 \end{bmatrix} \right) + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

$$\begin{bmatrix} F_a \\ T_a \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_0] \begin{bmatrix} 1 & R(a) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_0] \begin{bmatrix} \omega \times (\omega \times -a) \\ 0 \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

So that we can say in general a change of coordinates yields a change in the mass parameters as follows,

$$[M_a] = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_0] \begin{bmatrix} 1 & R(a) \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{v}_a \\ \dot{\omega}_a \end{bmatrix}$$

$$\begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_0] \begin{bmatrix} -R^2(\omega)a \\ 0 \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

The same kind of derivation can be carried out for a rotational transformation of coordinates represented by a rotational transformation matrix, C, as follows. C is the matrix talking coordinates in frame c to some base frame **0**, so that the basic transformational rules for a rotation in matrix form

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} F_c \\ T_c \end{bmatrix}; \quad \begin{bmatrix} F_c \\ T_c \end{bmatrix} = \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} \begin{bmatrix} F_0 \\ T_0 \end{bmatrix}$$

-continued

$$\begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix} = \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} \dot{v}_c \\ \dot{\omega}_c \end{bmatrix}; \quad \begin{bmatrix} \dot{v}_c \\ \dot{\omega}_c \end{bmatrix} = \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix}$$

Then perform a similar manipulation f

$$\begin{bmatrix} F_0 \\ T_0 \end{bmatrix} = [M_0] \begin{bmatrix} \dot{v}_0 \\ \dot{\omega}_0 \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

$$\begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} F_c \\ T_c \end{bmatrix} = [M_0] \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} F_c \\ T_c \end{bmatrix} + \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

$$\begin{bmatrix} F_c \\ T_c \end{bmatrix} = \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} [M_0] \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix} \begin{bmatrix} F_c \\ T_c \end{bmatrix} + \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

so that the mass parameters transform as follows:

$$[M_c] = \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} [M_0] \begin{bmatrix} C & 0 \\ 0 & C \end{bmatrix}; \quad \begin{bmatrix} f_{0c} \\ t_{0c} \end{bmatrix} = \begin{bmatrix} C^T & 0 \\ 0 & C^T \end{bmatrix} \begin{bmatrix} f_{00} \\ t_{00} \end{bmatrix}$$

Force, torque input at a point:

Suppose a force F_a and torque T_a act at a point a for a duration, dt. Then the change in body centered linear momentum dP_0 and body centered angular momentum, dH_0 will be given by,

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} F_0 \\ T_0 \end{bmatrix} dt$$

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \begin{bmatrix} F_a \\ T_a \end{bmatrix} dt$$

Velocity delta input at a point:

Suppose the environment imposes a instantaneous change in the velocity at a point of dv_a and $d\omega_a$. Then the change in body centered linear momentum, dP_0 and body centered angular momentum, dH_0 will be given as follows. First rewrite the basic mass equation at a point so that

$$\begin{bmatrix} F_a \\ T_a \end{bmatrix} dt = [M_a] \begin{bmatrix} dv_a \\ d\omega_a \end{bmatrix} + \begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix} dt$$

This can be used in the basic momentum equation, above, so that

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \begin{bmatrix} F_a \\ T_a \end{bmatrix} dt$$

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_a] \begin{bmatrix} dv_a \\ d\omega_a \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix} dt$$

Taking the limit as dt→0 yields,

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} [M_a] \begin{bmatrix} dv_a \\ d\omega_a \end{bmatrix}$$

Velocity delta plus zero torque input at a point:

When the input is linear velocity and there is no torque in the interface, the equations must be rewritten to solve for force and angular acceleration in terms of linear acceleration and torque, then converted to changes in momentum at the object center. To do this, break down the mass parameter matrix M_0 into parts, i.e.

$$\begin{bmatrix} F_a \\ T_a \end{bmatrix} dt = \begin{bmatrix} M_{a11} & M_{a12} \\ M_{a21} & M_{a22} \end{bmatrix} \begin{bmatrix} dv_a \\ d\omega_a \end{bmatrix} + \begin{bmatrix} f_{0a} \\ t_{0a} \end{bmatrix} dt$$

Let the f_{0a}dt and t_{0a}dt go to zero, but $F_a$dt and $T_a$dt remain finite, the rearrange to get,

$$\begin{bmatrix} 1 & -M_{a12} \\ 0 & -M_{a22} \end{bmatrix} \begin{bmatrix} F_a dt \\ d\omega_a \end{bmatrix} = \begin{bmatrix} M_{a11} & 0 \\ M_{a21} & -1 \end{bmatrix} \begin{bmatrix} dv_a \\ T_a dt \end{bmatrix}$$

Invert the first matrix and multiply on both sides to get,

$$\begin{bmatrix} F_a dt \\ d\omega_a \end{bmatrix} = \begin{bmatrix} 1 & -M_{a12} M_{a22}^{-1} \\ 0 & -M_{a22}^{-1} \end{bmatrix} \begin{bmatrix} M_{a11} & 0 \\ M_{a21} & -1 \end{bmatrix} \begin{bmatrix} dv_a \\ T_a dt \end{bmatrix}$$

$$\begin{bmatrix} F_a dt \\ d\omega_a \end{bmatrix} = \begin{bmatrix} M_{a11} - M_{a12} M_{a22}^{-1} M_{a21} & M_{a12} M_{a22}^{-1} \\ -M_{a22}^{-1} M_{a21} & M_{a22}^{-1} \end{bmatrix} \begin{bmatrix} dv_a \\ T_a dt \end{bmatrix}$$

Pull out the terms that are needed and transform to body centered coordinates to get,

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \begin{bmatrix} M_{a11} & M_{a12} \\ M_{a21} & M_{a22} \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -M_{a22}^{-1} M_{a21} & M_{a22}^{-1} \end{bmatrix} \begin{bmatrix} dv_a \\ T_a dt \end{bmatrix}$$

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R(a) & 1 \end{bmatrix} \begin{bmatrix} M_{a11} - M_{a12} M_{a22}^{-1} M_{a21} & M_{a12} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} dv_a \\ T_a dt \end{bmatrix}$$

which, when $T_a$dt is zero, has the simple representation,

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 \\ R(a) \end{bmatrix} [M_{a11} - M_{a12} M_{a22}^{-1} M_{a21}][dv_a]$$

For a single link with no other connections, we have

$$[M_a] = \begin{bmatrix} m_0 & m_0 R(a) \\ R(a) m_0 & I_0 \end{bmatrix}$$

so that

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 \\ R(a) \end{bmatrix} [m_0 - m_0 R(a) I_0^{-1} R(a) m_0][dv_a]$$

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} 1 \\ R(a) \end{bmatrix} [m_0 + (R(a) m_0)^T I_0^{-1} (R(a) m_0)][dv_a]$$

Reverting back to cross product notation, this is,

$$\begin{bmatrix} dP_0 \\ dH_0 \end{bmatrix} = \begin{bmatrix} m_0(dv_a + m_0(a \times (I_0^{-1} \otimes (a \times dv_a)))) \\ a \times m_0(dv_a + m_0(a \times (I_0^{-1} \otimes (a \times dv_a)))) \end{bmatrix}$$

PID control of massy link in one degree of freedom:

Equations of motion for simple mass with PID control are,

$$\dot{p} = x;\ \dot{x} = v;\ \dot{v} = \frac{1}{m} \sum f = \frac{1}{m}(g - av - bx - cp)$$

where x is a position, v is a velocity, and p is an integral-error term. Here, g is an external input force. The values a, b, and c represent the controller, and are chosen to provide a desired closed-loop response of the system.

The transfer function for this system is,

$$\frac{P(s)}{G(s)} = \frac{1/m}{s^3 + \frac{a}{m}s^2 + \frac{b}{m}s + \frac{c}{m}}$$

with s representing the Laplacian operator, d/dt. By choosing a, b, and c as follows,

$$a=3m/\tau;\ b=3m/\tau^2;\ c=m/\tau^3$$

the system will have three real roots at $s=-1/\tau$ so that the general solution in terms of p will be,

$$p(t)=Ae^{-t/\tau}+Bte^{-1/\tau}+Ct^2e^{-1/\tau}$$

Notation is simplified by introducing a variable u, so that the other state variables can be computed as derivatives of the above equation to get the solution at a time, t,

$$u=e^{-t/\tau}$$

$$p(t)=Au+Btu+Ct^2u$$

$$x(t)=-Au/\tau+Bu-Btu/\tau+2Ctu-Ct^2u/\tau$$

$$v(t)=Au/\tau^2-2Bu/\tau+Btu/\tau^2+2Cu-4Ctu/\tau+Ct^2u/\tau^2$$

At t=0, the above equations reduce to,

$$p(0)=A;\ x(0)=-A/\tau+B;\ v(0)=A/\tau^2-2B/\tau+Cr^2u/\tau^2$$

From the above initial conditions, $p_0=p(0), x_0=x(0), v_0=v(0)$, the particular solution has coefficients,

$$A=p_0;\ B=p_0/\tau+x_0;\ C=-p_0/\tau^2+x_0/\tau v_0/2$$

These can be substituted into the previous equations to compute the particular solution given arbitrary state and constant control coefficients. In particular, for large simulation time steps, the effects of a system under PID control can be simulated in closed form without loss of accuracy due to approximations.

Finally, it should further be appreciated that the inventive approach also facilitates more refined constructions, such as joints **28** that have limited movement, highly non-linear joints **28** such as the string relationships existing in puppets, very springy joints **28** for comic effects, and simple implementation of joints **28** having variable stiffness, as occurs when animals are in different states of arousal or motivation, or even joints whose control properties are defined by stochastic rather than deterministic functional relationships.

Buoyancy Control of Motion:

When trying to simulate quadrupeds such as dogs, cats, elephants, and so on, problems often arise because most of their mass is above their feet. For lifelike simulation of quadrupeds, it is necessary that the simulated synthetic creature **10** occasionally move through positions that are statically unstable, such as when running, etc. and, unfortunately, such simulated creatures have a tendency to fall down easily. This problem, of course, becomes even more pronounced when simulating humans and other bipeds.

The classical approach to overcoming this problem has been to use closed loop control of the entire system. First, the system must be instrumented sufficiently for all of the state variables to be "observable," to use the terminology of control systems theory. Generally, this requires at least one measurement for each state variable. In a simulation, these quantities are directly available, but for a modest synthetic creature **10** with, say, twenty one links **26** this will still be 126 variables (6×21=126) to be observed. These measurements will be combined according to a control rule to control each of the twenty joints 28, or 120 degrees of freedom. Because of the kinematic linkages involved, a linear control rule here is inadequate, and solving the problem in toto quickly becomes impractical using this approach.

To solve this problem the inventors have turned to human-factors engineering, where a model called the crossover model is used. The crossover model states that when a human being is part of a control loop, (e.g., when controlling a car or an airplane) he or she will behave so that the closed loop behavior of the system is stable and consistent, regardless of the fact that it is actually an open loop system being controlled, subject to such human limitations as reaction time, strength, and so on. By using this model in the control of individual limb segments, or in the control of a complete system such as an animal, the inventors are able to achieve stable, computable control without sacrificing realism. Stated simply, because a simulated dog synthetic creature **10** will behave as if its head link **34** is buoyant, it is a sufficient and compelling simulation to provide buoyancy in its head link **34** for purposes of simulation. (See e.g., negative weight **48** in FIG. 4.)

To do this, for each link **26** the inventors separate the components of mass and weight, and treat them separately. Often these two concepts are confused by lay people, and the English system of measurement is still confounded by the same name for gravitationally-induced weight (pound-weight) and the tendency to stay at rest or in motion (pound-mass). While the metric system separates these into the Newton and the kilogram, people commonly measure their weight in "kilograms" using an ordinary household scale. The ability to separate weight and mass is further obscured by the fact that everyday life contains few objects having positive mass and negative weight. For example, a helium balloon has these properties, but its mass is negligible, and people are surprised when a helium balloon in an accelerating bus moves forward due to its buoyancy relationship to the surrounding air.

In the inventors' approach to simulation, links **26** that are normally controlled to remain near the ground are given additional positive weight **46** (depicted by arrows), while links **26** controlled to remain high, such as the head link **34**, are given negative weight **48** (also depicted by arrows). If the weight increments added and subtracted sum to zero, there will be no net weight added to the group of links **26**, and their macroscopic behavior within the environment will remain realistic. Further, pairs of positive weight **46** and negative weight **48** can be added to the same link **26** to provide a torque-based buoyant property (see e.g., the head link **34** in FIG. 4). This is suitable, for example, for the control of the head link **34** of a synthetic creature **10**, since most real animals would prefer, and are expected, to keep their head in an upright position, insofar as possible.

The Actions of a Synthetic Creature:

Actions **18** are primitives which a synthetic creature **10** is capable of. Major examples include movements **50** and noises **52**, although other types of actions **18** are also possible (e.g., special communications, or appearances, such as the blush on the face of a clown synthetic creature **10** as it realizes it has done something embarrassing). A point to appreciate here is that categorizing specific actions **18** (e.g., whether a bark is a mere noise, or a message to stay away, or a message to come play) is not critically important. What is important is that authoring a collection of possible actions **18** for a synthetic creature **10** produces a library of useful primitives from which the more complex behaviors **20** may later be built.

In practice, most actions **18** are movements **50**, sequences of poses **58** separated by step times **60** and governed by the character **16** and the universe **14**. A pose **58** is a desired geometry of the links **26** and joints **28** of a synthetic creature **10**. As a definitional convenience the inventors also treat single poses **58** as movements **50**, and define the normal pose **59** of an action **18** as the pose **58** first dictated by the geometry of the character **16**.

FIG. **5** is a stylized time-line and icon depiction of a typical dog synthetic creature **10** jumping. Pose0 **58*a*** is the synthetic creature **10** in a normal pose **59**. After step0 **60*a*** the synthetic creature **10** is at pose1 **58*b***,rocked back on its rear legs. After step1 **60*b*** the synthetic creature **10** is at pose2 **58*c***, hunched down on its front legs. After step2 **60*c*** the synthetic creature **10** is at pose3 **58*d***, all legs extended as it springs through the air. After step3 **60*d*** the synthetic creature **10** reaches pose4 **58*e***, landing with all legs flexed slightly to absorb the impact. And, finally, after step4 **60*e*** the synthetic creature **10** reaches pose5 **58*f***, a general finishing position (which might even be the same as normal pose **59** also, although many implementations will have a number of slightly different general poses **58**, to enhance the lifelike appearance of the overall synthetic creature **10**).

Noises **52** are another key type of action **18**. An example of a noise **52** might be an "umh" as a dog synthetic creature **10** runs into something. Noises **52** are dealt with in the preferred embodiment by playback of pre-recorded sound files, which may be in conventional computer formats (e.g., WAV or MIDI type sound files).

The Behaviors of a Synthetic Creature:

Intelligent behaviors **20** for synthetic creatures **10** are created as sets of cooperating and competing processes, which give a feeling of autonomy and awareness, as well as properties such as graceful degradation and variability which are difficult to achieve using prior techniques. By using this approach, and particularly the other simulation described technologies herein, computation can be drastically reduced over current methods, making it possible for the first time to create a real-time simulation of a moderately complex animal using personal computers.

Behaviors **20** are how users ultimately perceive the composite activities of a synthetic creature **10**. An example of a behavior **20** might be a synthetic creature **10** chasing a ball. Such a behavior **20** would encompass, at an abstracted level, actions **18** like running, turning, and barking, which themselves are an abstracted level above the character **16**, which specifies such details as the range of motion of limbs and the springiness of joints (i.e., links **26** and joints **28**).

To define the overall behavior **20** of a synthetic creature **10** (i.e., its brain) the inventors use a behavior tree **72** hierarchy of optionally recursive sub-behaviors **74** composed of behaviors **20** and actions **18** (see e.g., FIG. **18** and FIG. **19**, discussed in detail under implementation below). The overall behavior **20** of a synthetic creature **10** is manifested by execution beginning at the root of the behavior tree **72**, and progressing through branches until leafs are reached (i.e., ultimately actions **18**). In the inventors' scheme sub-behaviors **74** are typed as sequential sub-behavior **76**, parallel sub-behavior **78**, decision sub-behavior **80**, and interruptible sub-behavior **82**. Of course, other types can be implemented, if desired, but conceptually all situations encountered to date seem to be addressable as tree branches composed recursively of these four types. For example, planning and recognition are implimentable as constructs using decision sub-behaviors **80**. In particular, a synthetic creature **10** with extensive learning capabilities will in all likelihood require the ability to add or remove behaviors **20** to develop totally new behaviors **20** on its own (i.e., a form of learning).

Sequential sub-behaviors **76** are represented as ordered lists of sub-behaviors **74**, which in turn may be other sub-behaviors **74**. For sequential sub-behaviors **76** the order of the sub-behaviors **74** within the list determines the order of their execution. Parallel sub-behaviors **78** are representable as non-ordered (i.e., ordering is irrelevant) lists of sub-behaviors **74**, where all of the branch sub-behaviors **74** in the list execute concurrently.

Decision sub-behaviors **80** are also representable as non-ordered lists, but lists of sub-behaviors **74** which each are initially (in the preferred embodiment) giving an equal weighting factor **88**, and for which the weighting factor **88** may then be author adjusted. Upon beginning execution of a decision sub-behavior **80**, a random selection is made based on a probability distribution given by the combination of the weighting factor **88** and evaluated to determine which sub-behavior **74** is executed. Using this very simple principle decision sub-behaviors **80** can accomplish quite complex results (e.g., personality). To appreciate this concept one need merely appreciate that reality is random and, accordingly, modeling reality requires some randomness as an input.

Interruptible sub-behaviors **82** are represented as a default sub-behavior **90** and an ordered list of paired key stimuli **92** and associated sub-behaviors **94**. Upon beginning execution of an interruptible sub-behavior **82**, all of the key stimuli **92** are evaluated and the first associated sub-behavior **94** having its corresponding key stimuli **92** set is executed. If no key stimuli **92** is set, the default sub-behavior **90** is executed.

An example of a partial behavior tree **72** for a cat synthetic creature **10**, which illustrates sub-behaviors **74**, might be:

```
Main behavior (interruptible)
    <null> Sleep (parallel)
    <roosterCrow> Wake (parallel)
        EyeBlinking (sequential)
        WakingActivity (interruptible)
            <null> WatchFish (sequential)
                    GoToFishBowl (sequential)
                    GazeAtFish (sequential)
                    RespondToFish (decision)
                        BatAtBowl (sequential) [1]
                        DipInBowl (interruptible) [1]
            <nameCall> RespondToOwner (decision)
                GoToOwner (sequential) [5]
                WaitOwnerCome (parallel) [1]
                HideFromOwner (interruptible) [0.8]
    <mealCall> RunToKitchen (sequential)
```

In this example sub-behavior **74** types are noted in parentheses, key stimuli **92** are enclosed in "<" and ">" symbols (with "<null>" opposite each default sub-behavior **90**), and values for weighting factors **88** are shown between square brackets. In the above example the decision sub-behavior **80** labeled "RespondToFish" has all equal weighting factors **88** for each sub-behavior **74**, as if the default

weighting factors **88** have not been adjusted. In contract, the decision sub-behavior **80** labeled "RespondToOwner" has different weighting factors **88** for each sub-behavior **74**, to increase the probability that the sub-behavior **74** labeled "GoToOwner" will run, and to decrease the probability that the sub-behavior **74** labeled "HideFromOwner" will run (i.e., this cat type synthetic creature **10** has a random attitude problem as part of its "personality").

In the above examples, rudimentary personality traits for a synthetic creature **10** were illustrated. Much more complex personalities are easily implemented with decision sub-behaviors **80**. For example, synthetic creatures **10** using the standard Myers-Briggs type personality preference variables to achieve very human like balances of extroversion vs. introversion, sensing vs. intuition, thinking vs. feeling, and judgment vs. perception. Further, it should now be readily apparent that other personality "engines" are also quite possible.

Process-based Intelligence.

While it is difficult to characterize current approaches to intelligence, an approach roughly equivalent to classical computer architecture may be useful for study. The simulated being is given a single, central controlling process, a set of tasks it can do, a stack frame, and a preemptive system for switching between tasks when new tasks come along. While this approach has merits, it also has limitations. First, such a system can only be doing one thing at a time, which results in a very computer-like appearance. Second, the system is subject to crashes. For example, when a single stack frame is out of order, all systems come to an immediate halt. Third, it is procedurally oriented, so it is difficult to impart high-level behaviors using these paradigms.

The inventors' approach avoids these problems by endowing the synthetic creature **10** with a set of independent behaviors **20** (i.e., processes; see e.g., FIG. **6** and FIG. **7**) that interact to achieve particular goals. Further, these behaviors **20** may be freely started or ended by other behaviors **20**, thus creating the recursive behavior tree **72** hierarchy structure of sub-behaviors **74** described above. For example, normally the function of an animal's body part depends upon the animal's behavior. At different times an animals head may be used for balance during walking, for gross pointing of the eyes when looking, or for communicating its wish for food or attention. In the inventors' approach, the independent behaviors **20** are used to control things such as head direction pointing, eye gaze, navigation, emotional state, and so on. By implementing intelligence in this way, the inventors achieve a kind of graceful degradation. When related behaviors **20** are missing because they have been destroyed or are not available yet, or are still in design and development, a specific behavior **20** can still operate to its new, limited, abilities. It has long been recognized that organic systems often have this property of graceful degradation, but it has been more difficult to achieve in mechanically based or artificial systems.

Variation is achieved when behaviors **20** can be started under some specific conditions, or different behaviors **20** are chosen at random to achieve the same goal, and under otherwise identical conditions.

By way of example, it is useful to study the interactions between gaze pointing, head pointing, and body positioning. Observing real animals shows us that when an interesting entity such as a fly is near the center of the visual field of a dog, say, then only the eyes are moved to view it. But, when the fly is farther afield, the head is also moved. And, when this is still not enough, the body is even moved, if necessary by first achieving a standing or sitting position.

In the typical computational approach to intelligence, to accomplish eye pointing one must simultaneously solve the problem of head pointing and body pointing. Further, when the animal is doing eye pointing, it will necessarily be doing head and body pointing as well. Also, typically, none of the eye pointing will be implemented and testable until all of the problem is solved.

In the inventors' process-based approach, as depicted in FIG. 6, the eye pointing behavior **98** consists only of pointing the eye links **36** if possible, or pointing the head link **34** if the object being viewed is too far afield. No details of the head pointing behavior **100** or the body pointing behavior **102** are needed to implement the eye pointing behavior **98**. During execution, the eye pointing behavior **98** proceeds whether the synthetic creature **10** is sitting or standing, walking or chasing, and there are no bottlenecks or processing conflicts to resolve. However, depicted in FIG. 7, if the head pointing behavior **100** is damaged or not finished yet (depicted as abnormal head pointing **104**), the eye pointing behavior **98** can still function, or at least be tested. It should also be appreciated that this approach may be useful for other aspects of intelligence to be modeled.

Stimuli and Environment Variables:

In the present invention stimuli **62** and environment variables **64** are used to control run-time execution of the behavior tree **72** of behaviors **20**. In programming terminology, stimuli **62** function as "flags" representing binary states such as true or false, on or off, etc. All stimuli **62** are associated with a world position **68**, which identify where within the environment **22** they originate at run-time. An example is a synthetic creature **10** perceiving a ball being present (i.e., it is either true or false that a ball is present). Since a world position **68** is associated with the stimuli **62** of the ball being present, the synthetic creature **10** is accordingly able direct its attention and ultimately also its behaviors **20**. In another example, a mouse click type stimuli **62** meaning to look at the user can have a user world position **68** (i.e., the screen or window into the synthetic creature's **10** world) for the synthetic creature **10** to turn toward.

In contrast, environment variables **64** are real number values which may further influence, dynamically at run-time, the likelihood that sub-behavior **74** which is part of a decision sub-behavior **80** will run (i.e., modifying the likelihood set during authoring by any weighting factor **88** applied by the author). An example of an environment variables **64** might be labeled "darkNight," and contain a real number value which is used to pass information about how dark the environment is to a decision sub-behavior **80** which controls a synthetic creature's **10** clumsiness.

The Environment of a Synthetic Creature:

Environments **22** are the particular physical and visual characteristics of surrounding space, including constraining surfaces such as floor and walls, distributed materials such as air and water, free fields such as gravity, and events such as a tree falling or an earthquake into which a synthetic creature **10** may be placed. Accordingly, environments **22** can become quite complex, although such complexity is not always necessary. In fact, in theory, a synthetic creature **10** may not have any environment **22**, although such a synthetic creature **10** would probably not be very satisfying to users. Further, a synthetic creature **10** may be placed in or even travel through multiple environments **22**. For example, one environment **22** might be authored to resemble a setting on earth, with a second to resemble a setting on the moon, these would be two valid environments **22** for a synthetic creature **10**, as long as the same universe **14** is used.

Noted in FIG. 1, the major components of environments **22** include a visual backdrop **106**, static objects **108**, and dynamic objects **110**. Of course, other components may easily be envisioned and implemented for use in environments **22**, but only these few will be discussed here, to facilitate understanding of the inventive synthetic creature **10**.

The visual backdrop **106** consists of a base surface **112** (e.g., ground if outside or a floor if inside a building) and a distance view **114**, which may either be merely a 360 degree panorama visible horizontally (i.e., there is no "up" view), or a true hemispherical full sky view. In the preferred embodiment, pre-recorded bit-maps are used for the base surface **112** and the distance view **114**.

Static objects **108** are distinct objects in the environment **22** which do not move. Examples include trees and walls. Static objects **108** require frequent calculation of a users view (i.e., is the static object **108** in front of or behind a synthetic creature **10**, or a dynamic object **110** at any particular instance; resembling a sprite problem). Static objects **108** also require spatial conflict resolution, since a synthetic creature **10** or a dynamic objects **110** may move in front of or in back of but not right through a static object **108** like a tree.

Unfortunately, these requirements introduce considerable run-time computer system rendering overhead. Therefore, for a simple environment **22** it is often easiest to leave out static objects **108**, and in some implementations the inventors have done exactly this, depicting a synthetic creature **10** only in an open park setting or on a beach (one without true wave action). Further, unfortunately, static objects **108** are often desired in relatively large numbers. For example, a forest, a maze, or a room full of pieces of furniture. Therefore, authors are often compelled to resort to visual tricks to limit the use of static objects **108**, like putting all trees or furniture into the distance view **114**, which the synthetic creature **10** then always passes in front of.

The inventors do not herein teach a direct solution to any of the above static object **108** problems, but it should be appreciated that use of the techniques taught herein to simulate efficient synthetic creatures **10** do free up run-time resources to be applied to this.

In contrast to static objects **108**, dynamic objects **110** move about within environments **22**. Some examples of dynamic objects **110** include toys for play, like balls, and other synthetic creatures **10**. A synthetic creature **10** can play with a ball dynamic object **110** either on its own or with its user. It can nudge a ball into motion and chase it, running in front of and behind it as needed. Or it can chase a ball moved by a user (say by a mouse click on the ball and a drag-toss action). Similarly, a first synthetic creature **10** can interact with other synthetic creatures **10** in an environment **22**. It should be noted that such multiple synthetic creature **10** interactions can be quite complex, for example involving not only positional messaging such s that of the chase-ball scenario, but also audible interaction, like barking or meowing, and even other types (e.g., odor interaction in a dog meets skunk scenario).

Dynamic objects **110** have the same closest-to-viewer and spatial-position-conflict concerns as static objects **108**. However, dynamic objects **110** are usually inherently used sparingly. Since too many independently active elements in a scene confuse viewers, authors usually only desire a few key dynamic objects **110**, to focus users view on the author's creative purpose. In most implementations to date, the inventors have not encountered a need for scenarios with more than two or three dynamic objects **110** at a time (however, this is not a limitation; larger numbers are certainly possible, if desired and where run-time resources can support them).

IMPLEMENTATION OF A SYNTHETIC CREATURE

The preceding section has dealt with the inventors' definition of a synthetic creature **10**. Implementation of that definition requires tools, i.e., an authoring environment **200** (not shown), for authors to apply the definition when creating synthetic creatures **10** in computer readable format, and a run-time computer **202** (also not shown) upon which to ultimately present a finished synthetic creature **10** to viewers.

The Authoring Environment:

As noted previously, the inventors have found that considerable programming efficiency may be obtained by generally authoring in distinct layers **12** (FIG. **1**). It therefore follows that distinct tools for each of the layers **12** are desirable (as contrasted to "required"; separation of tools is not absolutely necessary, and accordingly should not be regarded as a limitation on the true scope of the present invention). As illustrated in the various drawings, basic forms of the preferred embodiments of the tools are respectively depicted by the general reference character **204** for an optional universe editor (not shown); by the general reference character **206** for the inventive character editor (particularly shown in the views of FIG. **8** through FIG. **15***c*); the general reference character **208** for the inventive action editor (particularly shown in the views of FIG. **16** and FIG. **17**); the general reference character **210** for the inventive behavior editor (particularly shown in the views of FIG. **18** through FIG. **21**); and the general reference character **212** for the inventive environment editor (not shown).

The Optional Universe Editor:

As previously noted, the simplest way to author a universe **14** (FIG. **1**) is to simply "hard code" a physics **24**, (e.g., conventional "earth-normal" equations and coefficients) into the character **16** (more correctly, by integrating this ability into the character editor **206**, so that the physics **24** becomes a part of each character **16** as it is authored). Rather than use a separate universe editor **204**, that is what the inventors have done for all embodiments to date. However, it is but a small additional step to add a user interface to permit authors to change the physics **24** of the universe **14**, say by entering non-Newtonian equations or non-earth normal coefficients (i.e., physical constants, say for gravity, friction, or elasticity of materials).

Authoring of such a universe **14** would include entering or selecting from among already stored physical constants **214** (e.g., for gravity, friction, etc.), and entering or modifying already stored standard equations **216** (e.g., Newton's equations of motion), which will together govern motion of any object (i.e., not just the synthetic creature **10**) within that universe **14**.

The Character Editor:

In the preferred embodiment, the first major authoring task is creation of a character **16** for the synthetic creature **10** (i.e., the three dimensional physical model for a synthetic creature **10**, including shape, mechanics, and visual characteristics). This requires specifying characteristics of and relationships between links **26** (i.e., limbs) and joints **28**. A tool is needed to author new characters **16**, to edit existing characters **16**, and to test characters **16**, and in the preferred embodiment this role is filled by the character editor **206**.

FIG. **8** through FIG. **15***c* depict various screen-captures taken from a typical character editor **206** in use. Turning now particularly to FIG. **8**, the character editor **206** presents an author with a character editor screen **218** which at its top includes an information bar **220** and a menu bar **222**. A synthetic creature **10** is built up by entering link **26** and joint **28** associations centered in the character editor screen **218** above a floor grid **224** and initially centered on a vertical plane grid **226** with a horizon line **228** across the background. Further appearing when an existing link **26** is double-clicked on with a mouse or hot-key selected is a character properties window **230** (FIG. **9**), which is author dragable anywhere within the character editor screen **218**.

FIG. **9** illustrates the major elements of the character properties window **230**, including color properties sliders **232**, a joint type button set **234**, name line-list **236**, visual characteristics checkboxes **238**, joint characteristic lines **240**, link physics characteristic lines **242**, and link construction characteristic lines **244**.

The color properties sliders **232** control hue, saturation, and brightness. Initial color selection is done with choices in the menu bar **222**, or setting a default. Once a color is used for one link **26** the next link **26** created automatically has a slightly different color, to distinguish closely adjacent links **26**. Color is freely further author changeable, via controls in the menu bar **222**.

The joint type button set **234** provides author selection of mechanical types of links **26**, including attached (i.e. rigidly connected to a higher order link **26** (e.g., the joint **28** joining a child link **32** to a non-associated link **30** in FIG. **10**), jointed (positionably rotatable about one or more axis), dynamic (simulating basic movement), and massy (having fully modeled movement characteristics).

The name line-list **236** provides a drop-down selection list of common labels for body parts (e.g., head, left shoulder, etc.), but with author ability to add new labels. The use of standardized labels, preferably conventional ones, permits reusability and portability of authoring work product across the layers **12**. For example, cat synthetic creature **10** type actions **18** and sub-behaviors **74** can be transferred to a dog synthetic creature **10** by using such common labels.

The visual characteristics checkboxes **238** permit selection of shaded, opaque, and invisible visual representation of a selected link **26**. Note that these are representations of the links **26**, not necessarily the ultimate visual characteristics which a user will see. Those may be modified by the texture **252** or by lighting provided in the environment **22** at run-time. In the inventors' preferred embodiment, such representations are used to specify some link **26** physical capabilities. Links **26** represented as visually shaded (see e.g., shade **246** in FIG. **14**) also pass through one another. In contrast, opaque links **26** cast a visible shadow (see e.g., shadow **248** in FIG. **11**) and can collide with other links **26** (i.e., be aware of other links **26**, and not occupy the same space). Invisible type links **26** are not visible, making them useful to add hidden mechanical properties, and thus obtain often novel results.

The joint characteristic lines **240** provide control of slide speed (transitional movement speed of a link **26**), screw speed (rotational movement speed of a link **26**), and restore time of a link **26** (much like some conventional muscle structure has different speeds of extension and retraction; this is only made available for the massy link type). The link physics characteristic lines **242** control density and buoyancy of the selected link **26**.

The link construction characteristic lines **244** control mesh **250** and texture **252** of the link **26**. The default mesh **250** of links **26** in the preferred embodiment is ellipsoid (see e.g., the visible mesh **250** in FIG. **15***a*). However, this is author changeable, say to trapezoidal, or dolphin shaped as is shown in FIG. 15*b*, and which underlies the example of texture 252 presented in FIG. 15*c*. Considerable structural shape variation is representable out of conventional mesh type constructs, and the present invention is fully capable of using such. (It should particularly be noted that while most examples presented in the figures use ellipsoids for simplicity, many implementations of synthetic creatures 10 will use more sophisticated mesh 250. Texture 252 is a conformal mapping over the surface of a link 26 (e.g., the bitmap "wrapped" over the dolphin synthetic creature 10 appearing in FIG. 15*c*). Texture 252 is quite useful for imparting a "skin" to a synthetic creature 10, and some sophisticated examples being fur and reptile scales. (Here also, few examples of texture 252 are present in the figures, but those skill in the relevant arts will readily see that the present invention is capable of very broad application of texture 252.)

Many features of the preferred embodiment of the character editor 206 are accessed with hot-keys and click and drag mouse operations. For example, in FIG. 8 a user has clicked and dragged to size a link 26. In FIG. 10 a second link 26 has been added (both links 26 are shown as mere ovals here to emphasize the joint 28), and a double click and drag operation has been used to add a joint 28 between the links 26 (actually making one a child link 32 and the other a non-associated link 30 at this point). In FIG. 11 left side front and rear foot links 42 have been added. In FIG. 12 the author has rotated the view in the character editor screen 218 (via a hot-key access to a camera button matrix; such are described in more detail for the action editor 208 and the behavior editor 210, below) and symmetrically copied the left side foot links 42 to create right side foot links 42 also. In FIG. 13 basic head link 34 sub-structure is added to the synthetic creature 10, and in FIG. 14 the full synthetic creature 10 is structurally complete.

The Action Editor:

To implement the inventors' definition of a synthetic creature 10 a tool is also needed to author new actions 18, to edit existing actions 18, and to test actions 18. In the preferred embodiment of the present invention this role is filled by an action editor 208. As previously discussed, actions 18 are organized into and stored in (unordered) lists. In the inventors' presently preferred embodiment, the only actions 18 handled in the action editor 208 are movements 50. Although noises 52 are conceptually also actions 18, they are specified later in the behavior editor 210. One rationale for this is that the ability to enter, change, and test noises 52 only has usefulness to authors at the layer 12 of behaviors 20. However, it should be appreciated that this is a matter of design preference, and that noises 52 and even other types of actions 18, as might be custom defined for special implementations, could be handled by other straightforward implementations of the action editor 208.

FIG. 16 and FIG. 17 depict screen-captures taken of a typical action editor 208 in use. In FIG. 16 the action editor 208 presents an author with an action editor screen 254 which at its top includes an information bar 256 and a menu bar 258. Once loaded (by opening a file containing a definition of character 16), a synthetic creature 10 appears centered in the action editor screen 254 above a floor grid 260 and with a horizon line 262 across the background. Further appearing, and author dragable anywhere within the action editor screen 254, is a keypose controls window 264.

FIG. 17 shows the keypose controls window 264 of FIG. 16 in more detail. The preferred keypose controls window 264 includes five major groups of sub-controls, including a

pose controls group 266, an action controls group 268, a stepping controls group 270, a simulation controls group 272, and a camera controls group 274.

The preferred pose controls group 266 provides author control over individual pose 58 details, and includes a pose id line 276, a pose id list 278, a create pose button 280, a reset pose button 282, and a delete pose button 284. The name of the current pose 58 of the current action 18 is presented in the pose id line 276, and an ordered list of poses 58 (FIG. 17) is presented in the pose id list 278. Appropriate selection (e.g., via a conventional selection mechanism like double-clicking with a mouse, or scrolling and pressing an enter key) of a pose 58 in the pose id list 278 makes that pose 58 the selected pose 58, and makes its name appear in the pose id line 276. If the list exceeds the space available, the pose id list 278 becomes scrollable. (In the figures, the pose id line 276 and the pose id list 278 somewhat appear to be one, however they are functionally distinct.)

Creation of a new pose 58 for the presently selected action 18 is accomplished by pressing the create pose button 280. In the preferred embodiment poses 58 are automatically named pose0, pose1, pose2, etc. Therefore, once the create pose button 280 is pressed a new name appears in the pose id line 276. The author then clicks and drags links 26 of the current pose 58 of the synthetic creature 10 in the action editor screen 254 until satisfied with the pose 58. Double clicking the pose id line 276 saves the present pose 58 into the presently selected action 18, a new pose 58 is placed after the presently selected pose 58. At any point prior to this save operation an author may press the reset pose button 282, to start over with the links 26 of the synthetic creature 10 in their original normal pose 59. However, after this save operation an author must either use the delete pose button 284 to remove a selected pose 58 or else edit the pose 58. Editing of existing poses 58 is accomplished by selecting the desired pose 58, clicking and dragging the links 26 where desired, and resaving the pose 58.

The preferred action controls group 268 provides author control over details of individual actions 18, and includes an action id line 286, an action id list 288, a new action button 290, a group actions button 292, and a clone action button 294. Similar to the pose controls group 266, the name of the current action 18 and an ordered list (scrollable if large) of the actions 18 for current the synthetic creature 10 are presented. Selection of actions 18 may also be done similarly.

Creation of a new action 18 is accomplished by pressing the new action button 290. A default name for the action 18 is presented (e.g., action0, action1, etc.), but unlike poses 58 the name of an action 18 is editable in the action id line 286. The author may then create poses 58 for the action 18 with the pose controls group 266, ultimately double clicking on the action id line 286 to save the action 18. Note however that no step times 60 have been specified yet. In the preferred embodiment a default step time 60 is provided between all poses 58, and individual step times 60 are later tuned by the author as desired. Predictably, editing of existing actions 18 is done by selection and use of the pose controls group 266. The group actions button 292 combines a group of existing poses 58, selected in the pose id list 278, into a new action 18 (an authoring convenience, since many actions are quite similar). The clone action button 294 copies a selected action 18 into a new action 18, which is given a default name until the author changes it in the action id line 286.

The preferred stepping controls group 270 and simulation controls group 272 work partially in concert. The stepping controls group **270** includes a step forward button **296**, a step backward button **298**, a toggle pose button **300**, a simulate forward button **302**, and a simulate backward button **304**. The simulation controls group **272** includes a step speed line **306**, a step speed slider **308**, a start simulation button **310**, a stop simulation button **312**, and a reset simulation button **314**.

An author may step through the poses **58** of an action **18** by using the step forward button **296** and the step backward button **298**. Such stepping, however, merely presents poses **58** in snapshot fashion. To see an action **18** played back in motion picture fashion (i.e., engaging the full characteristics of the character **16** and the universe **14**), the author uses the simulate forward button **302** and the simulate backward button **304**. Finally, the toggle pose button **300** toggles between the two most recent poses **58**, a redundant capability, but a single button authoring convenience.

An author tailors step times **60** between individual poses **58** in a selected action **18** by either operating the step speed slider **308** or directly editing the value displayed in the step speed line **306** of the simulation controls group **272**. Usually authors want to try several values, and thereby "tune" step times **60**. This is where many authors appreciate the toggle pose button **300**. The start simulation button **310**, stop simulation button **312**, and reset simulation button **314** control simulation of an entire selected action **18**.

Finally, the camera controls group **274** includes a view selection button matrix **316**, which predictably controls orientation of an author's view of the synthetic creature **10** in the action editor screen **254**.

The Behavior Editor:

To implement the inventors' definition of a synthetic creature **10** a tool is also needed to author new behaviors **20**, to edit existing behaviors **20**, and to test behaviors **20** of a synthetic creature **10**. In the preferred embodiment, this role is filled by a behavior editor **210**. As previously discussed, behaviors **20** are organized into and stored as a behavior tree **72** of optionally recursive sub-behaviors **74**. Some possible types of sub-behaviors **74** are actions **18** (e.g., movements **50**), a sequential sub-behavior **76**, a parallel sub-behavior **78**, a decision sub-behavior **80**, and an interruptible sub-behavior **82**. However, this list should not be interpreted restrictively. To date the inventors have found these types adequate for their needs, but other pre-defined types are quite possible, and for some behavior editor **210** implementations perhaps desirable, even if only as an authoring convenience.

FIG. **18** depicts a screen-capture of a typical behavior editor **210** in use. The behavior editor **210** presents an author with a behavior editor screen **318** which at its top includes an information bar **320** and a menu bar **322**. Once a file of actions **18** is loaded (a conventional file open operation), a synthetic creature **10** appears centered in the behavior editor screen **318** above a floor grid **324** and with a horizon line **326** across the background (not shown due to the downward angle of view in this figure, an equivalent example is the horizon line **262** of the action editor **208** in FIG. **16**). The first pose **58** of the first action **18** of the loaded synthetic creature **10** is that initially presented. Further appearing, and each able to be dragged by the author anywhere within the behavior editor screen **318**, are a stimuli ball **328**, a behavior tree window **330**, a behavior properties window **332**, and a behavior controls window **334**.

The stimuli ball **328** is dragged by the author where any stimuli **62** is desired to occur for testing purposes (the environment **22** and the user will ultimately provide different actual stimuli **62** at run-time). As previously discussed, all stimuli **62** are treated as having a world position **68** within the environment **22**, and it is the position of the stimuli ball **328** which is used to simulate this during authoring.

FIG. **19** shows a typical behavior tree window **330** in detail. The behavior tree window **330** will contain a depiction of a behavior tree **72** for a synthetic creature **10**, constructed out of various icons representing branches and leafs, and unique labels identifying sub-behaviors **74**. If a new behavior tree **72** is being opened (i.e., authored), only a root node **336** will be present. In the preferred embodiment a checkered flag icon **338** is used to represent the starting point of the currently selected sub-behavior **74**, which initially will be at the root node **336** of the behavior tree **72**. Right-pointing triangle icons **340** are used to represent collapsed branches, which each include a non-visible ordered list of multiple sub-behaviors **74**. Down-pointing triangle icons **342** are used to represent expanded branches, which each include a visible ordered list of multiple sub-behaviors **74**. Filled circle icons **344** are used to represent unique leafs, which each include a single primitive (i.e., non-recursive) sub-behavior **74** (but not merely an action **18**). Finally, clap-stick icons **346** are used to represent leafs which include only an action **18** (e.g., noises).

FIG. **20** shows the behavior properties window **332** in detail. The behavior properties window **332** permits an author to add sub-behaviors **74** to and edit existing sub-behaviors **74** in the behavior tree **72**. The behavior properties window **332** includes a behavior label line **348**, a behavior type list **350**, a behavior condition list **352**, a behavior condition value line **354**, a stimuli name line **356**, a behavior keyword list **358**, a behavior speed control sub-group **360**, a behavior reset checkbox **362**, a behavior attachment button **364**, and a behavior set-start button **366**. The behavior speed control sub-group **360** includes a behavior speed slider **368** and a behavior speed line **370**. Controls which are not available in particular scenarios are grayed out (not depictable in the line-art renditions used in the figures).

The label of a sub-behavior **74** is entered by the author into the behavior label line **348**. If the label is unique, creation of a new sub-behavior **74** is presumed. If the label matches one already in the present behavior tree **72**, editing of the matching sub-behavior **74** is presumed, and the other controls in the behavior properties window **332** will reflect present parameters for that sub-behavior **74**. Double-clicking a label in the behavior tree window **330** is also a way to "enter" that label into the behavior label line **348**, and thus to select that particular behavior **20** for editing. If the label entered is the name of a sound file (indicated by ".WAV" or another conventional sound file type file suffix in the preferred embodiment), a noise **52** becomes the entered sub-behavior **74**. The inventors' conceptually regard noise **52** as a form of action **18**, but for convenience handle them here in the behavior editor **210**.

In FIG. **19** and FIG. **20** the behavior type list **350** selection reflects that the "tapping" sub-behavior **74** is a parallel sub-behavior **78**. If a totally new (i.e., unique) label had been entered in the behavior label line **348** the author would have to specify a type of sub-behavior **74** from the behavior type list **350**.

The behavior condition list **352** and the behavior condition value line **354** provide for selection of how the sub-behavior **74** will perform. In the preferred embodiment, the behavior condition list **352** presents a list of conditions **372** (see e.g., FIG. **1**) types, which include a time condition **374**, a one-pass condition **376**, and a call-back condition **378**. If the time condition **374** is chosen, the sub-behavior **74** will run for a period of time specified by the author in the behavior condition value line **354**. Values are in seconds, with special cases such as zero used to indicate to not run a sub-behavior **74** (useful for testing), and negative one used to indicate that the sub-behavior **74** should run forever. If the selected sub-behavior **74**, including any possible lower branch sub-behaviors **74** (for example, the "dancing4" action **18** which is part of "tapping"), has not finished by the time specified in the behavior condition value line **354**, then its execution will be cut short. If a sub-behavior **74** finishes early it starts **30** over, and runs until time has expired. In contrast, the one-pass condition **376** specifies that the present sub-behavior **74** should execute exactly once. The behavior condition value line **354** is grayed out if a one-pass condition **376** is chosen.

It should be appreciated that implementing other special conditions **372** is quite possible. For example, a multi-pass condition, with the behavior condition value line **354** used to enter the number of passes, and perhaps with zero and negative values working as described above.

The call-back condition **378** is one of the inventors' catch all control provisions. It is where special conditions **372** may be implemented with customized modules. Users may enter or select and pass control information to specific call-back conditions **378** using the behavior keyword list **358**. One example might be a "chaseBall" until "closeEnugh" situation, using a "chaseBall" sub-behavior **74** with a "closeEnugh" evaluation that is more complicated than the mere binary yes vs. no state change of a stimuli **62**. Examples of typical keyword information might by strings like "right" or "up."

The stimuli name line **356** is grayed out except when an interruptible sub-behavior **82** is selected. This type of sub-behaviors **74** requires author entry of text identifiers for specifying stimuli **62** to act as key stimuli **92**. Since stimuli **62** are not evaluated until run-time, any text string can be used, and if such a string is not set by the environment **22** at run-time the associated sub-behavior **94** will be ignored.

For decision sub-behaviors **80** the behavior attachment button **364** is used to open a menu (not shown) of available sub-behaviors **74** and to select one to attach to the decision sub-behavior **80**. In the currently preferred embodiment of the behavior editor **210**, probability (determined at run-time) is used to determine which attached sub-behavior **74** will run, with all attached sub-behaviors **74** in a decision sub-behavior **80** initially assigned equal probability. However, the author may override this by selecting an attached sub-behavior **74** and modifying its weighting factor **88**, which will appear in the behavior condition value line **354**. A weighting factor **88** of zero may be entered in the behavior condition value line **354** to insure that a particular sub-behavior **74** in a decision sub-behavior **80** will not run, which is useful for testing purposes.

Particular parameters for action **18** type sub-behaviors **74** may be set with the behavior speed control sub-group **360**. For example, if the "singing" sub-behavior **74** (FIG. **19**) is selected, the behavior speed control sub-group **360** and the behavior reset checkbox **362** would cease to be grayed out. The author could then use the behavior speed slider **368** or manual text editing in the behavior speed line **370** to change the execution time. The behavior reset checkbox **362** is used to request that links **26** of the synthetic creature **10** be reset to the "pose0" pose **58** of the action **18** before it begins execution.

Finally, the behavior set-start button **366** moves the checkered flag icon **338** to the highlighted current sub-behavior **74** (FIG. **18**) in the behavior tree window **330**, making it a test starting point. (In the inventors' preferred embodiment the behavior set-start button **366** is in the behavior properties window **332**, but it could just as easily be placed in the behavior controls window **334**, or elsewhere.)

FIG. **21** shows the behavior controls window **334** in detail. The preferred behavior controls window **334** includes a simulation sub-control group **380**, a camera sub-control group **382**, and a stimuli sub-control group **384**. The simulation sub-control group **380** includes a simulation start button **386**, a simulation stop button **388**, and a simulation reset button **390**. In predictable fashion, an author may use the simulation sub-control group **380** to execute either the entire behavior tree **72** or the sub-behavior **74** which is selected as the current test starting point, and watch the synthetic creature **10** carry out the behavior **20** in the behavior editor screen **318**. To facilitate authors being able to see relevant aspects of the synthetic creature **10** under test, the camera sub-control group **382** changes the direction of view of the synthetic creature **10** (a view selection button matrix **392** is used, in similar manner to use of the camera controls group **274** in the action editor **208**). Finally, the stimuli sub-control group **384** is a stimuli generate button **394**. This opens a scroll box of stimuli **62** (the present type of sub-behavior **74** must be either a decision sub-behavior **80** or an interruptible sub-behavior **82**, or this will have no effect). Double-clicking a label for a stimuli **62** triggers it and causes it to be perceived as originating at the current location of the stimuli ball **328** (recall that an author user may drag this anywhere in the behavior editor screen **318**).

The Environment Editor:

To implement the inventors' definition of a synthetic creature **10** one or more tools are desired to author new environments **22**, to edit existing environments **22**, and to test environments **22** of a synthetic creature **10**. In the preferred embodiment, these roles are filled by a package of tools which will here be termed the environment editor **212**.

In the inventors' preferred embodiment the environment editor **212** functions largely as a tool to integrate existing elements into environments **22**, and to specify how the environment **22** produces stimuli **62**. For example, bit-maps are needed for the visual backdrop **106** (e.g., for the ground or floor shown in a base surface **112** and background scenes and walls shown In a distance view **114**). Off-screen sound s may also be desired as part of the environment **22**. Excellent tools for producing bit-maps and sound files already exist and are widely available, so the inventors' preferred environment editor **212** is used for integrating pre-defined elements into environments **22**. As previously noted, all stimuli **62** have an associated world position **68**. In the environment editor **212** authors are able to define where such world positions **68** will be at run-time, for example tying them to static objects **108** and even dynamic objects **110**.

Environments **22** can vary in complexity from effectively non-existent to quite complex (technically the action editor screen **254** and the behavior editor screen **318** are environments **22**). However, using the previously described techniques, development of the layers **12** below the environment **22** (e.g., characters **16**, actions **18**, and behaviors **20**) are abstracted out, thus relieving authors of the need to concern themselves with environments **22** until necessary (if ever, since environments **22** for synthetic creatures **10** might become a commodity, purchased from vendors for authors to use or for users to play or work with their synthetic creatures **10** in).

The Run-time computer:

A key goal of the present invention has been to permit use of synthetic creatures **10** on conventional computer systems today, and, in large, this means personal computers (say four megabytes of memory and a 32-bit processor, although more powerful engineering type workstations and even mainframe type computers can of course be used as well). That goal is met due to the efficient characters **16**, actions **18**, and behaviors **20** for synthetic creatures **10** which are now possible with the present invention.

In addition to the above mentioned examples, various other modifications and alterations of the synthetic creature **10**, the universe editor **204**, the character editor **206**, the action editor **208**, the behavior editor **210**, and the environment editor **212** may be made without departing from the spirit of the present invention.

INDUSTRIAL APPLICABILITY

The present synthetic creature **10** is well suited for application in real-time computer generated amusements. The inventors have worked considerably with synthetic creatures **10** for the purposes of developing "virtual pets," finding that they exhibit very life-like and amusing capabilities which makes them desirable to users, yet that they also run well on even personal computer systems having what are today regarded as conventional memory and processor resources.

The present synthetic creature **10** is also well suited for application in highly complex applications, such as computer graphics, cartoon drafting, computer game scripting, advertising, complex simulations of living organisms, and imparting life-like characteristics to simulations of physical objects. Further, while many of these applications are also in the general category of amusements, the present invention may also be widely applied as a teaching tool. Aside from the more obvious application to teaching of computer graphics and simulation technique, the synthetic creature **10** may also used to teach principles of physics, mechanics, dynamics, anatomy, and control theory.

The present authoring tools (i.e., the universe editor **204**, the character editor **206**, the action editor **208**, the behavior editor **210**, and the environment editor **212**) are well suited for application in developing the inventive synthetic creatures **10** and may also be applied to teaching computer graphics and simulation techniques.

Both the inventive synthetic creature **10** and the inventive authoring tools may be implemented on a large range of computer systems in use today, including personal computers, engineering type computer workstations, and mainframe computers. Further, both the inventive authoring tools and the inventive synthetic creature **10** may easily be adapted for use with computer networks, including the Internet. The present authoring tools are quite easily implemented for network server installation and remote network client use, much in the same manner that word processor and computer aided design programs are run on networks today. Simpler implementations of synthetic creatures **10** may even execute remotely yet be viewed locally, even with current network bandwidth limitations (e.g., the 28.8K baud modem access rate of many who today access the Internet). Virtually all implementations of the synthetic creature **10** should be transferable over networks. For example, a virtual aquarium might be stocked with virtual fish synthetic creatures **10**, with the owner able to log onto a remote "pet store" on the Internet, to add to their collection or replace pets who have "died" from old age or lack of owner interaction (i.e., virtual feeding and virtual affection).

For the above, and other, reasons, it is expected that the synthetic creature **10** and the authoring tools of the present invention will have widespread industrial applicability.

Therefore, it is expected that the commercial utility of the present invention will be extensive and long lasting.

What is claimed is:

1. A method of creating a synthetic creature simultation which runs on a computer system, the method comprising:

authoring a character for the synthetic creature by defining a link, and defining additional links and joining each said additional link to a previously defined said link with a soft joint; and

authoring a plurality of actions for the synthetic creature by positioning said character into a pose by moving said links into desired positions, and storing at least one said pose into each said action, to execute on the computer system.

2. The method of claim **1**, further including:

tailoring a set of link properties for each said link, including at least one member of the set consisting of link color properties, a link visibility property, link physical properties, and link skin properties.

3. The method of claim **2**, wherein:

said link color properties include at least one member of the set consisting of hue, saturation, brightness, reflectivity, and refractivity;

said link visibility property is chosen from the set consisting of shading opacity, invisibility;

said link physical properties include at least one member of the set consisting of shape, density, and buoyancy; and

said link skin properties include at least one member of the set consisting of mesh and texture.

4. The method of claim **1**, further including:

tailoring a set of joint properties for each said joint, including at least one member of the set consisting of joint type, and joint dynamics.

5. The method of claim **4**, wherein:

said joint type is chosen from the set consisting of attached, jointed, dynamic, and massy; and

said joint dynamics include at least one member of the set consisting of slide speed, screw speed, and restore time.

6. The method of claim **1**, further includes:

tailoring step times between sequential pairs of said poses within said actions.

7. The method of claim **1**, wherein:

a neutral pose is defined by authoring of said character; and further including:

tailoring a set of action properties for each said action, which includes whether said action resets to said neutral pose before running as part of the synthetic creature on the computer system.

8. The method of claim **1**, wherein:

authoring said actions includes specifying at least one computer recorded sound file.

9. The method of claim **1**, wherein:

said actions are stored in a library, and selectively retrieved from said library, for reusability when authoring said behavior trees.

10. The method of claim 1, wherein:

said character is a first character; and

said actions are stored in a library, and selectively retrieved from said library, and for reusability with a second character.

11. An tool for creating a synthetic creature with the method of claim 1, the tool comprising a computer system upon which a user authors said action.

12. A computer system executing a synthetic creature created with the method of claim 1.

13. The method of claim 1, further including:

authoring a behavior tree for the synthetic creature by defining behaviors by grouping instances of said actions and previously defined instances of said behaviors, and ordering said behaviors recursively into said behavior tree in a hierarchical structure which is executable on the computer system.

14. The method of claim 13, further including:

choosing a behavior termination condition from the set consisting of:

timed termination, which defines said behavior to execute until a period of time elapses;

single pass termination, which defines said behavior to execute only once; and

multiple pass termination, which defines said behavior to execute a specified number of times.

15. The method of claim 13, wherein:

said behaviors are stored in a library, and selectively retrieved from said library, for reusability when authoring said behavior trees.

16. The method of claim 13, wherein:

said character is a first character; and

said behaviors are stored in a library, and selectively retrieved from said library, for reusability with a second character.

17. An tool for creating a synthetic creature with the method of claim 13, the tool comprising a computer system upon which a user authors said behavior.

18. A computer system executing a synthetic creature created with the method of claim 13.

19. The method of claim 11, further including:

choosing said behaviors from the set consisting of sequential type behavior, parallel type behavior, interruptible type behavior, and decision type behavior.

20. The method of claim 19, wherein:

said sequential type behavior executes each of said behaviors and said actions grouped therein sequentially on the computer system.

21. The method of claim 19, wherein:

said parallel type behavior executes all of said behaviors and said actions grouped therein in parallel on the computer system.

22. The method of claim 19, wherein:

specifying said interruptible type behavior further includes the steps of specifying at least one stimuli-behavior pair by associating a key stimuli with an associated behavior, ordering said stimuli-behavior pairs, and specifying a default behavior; wherein

said interruptible type behavior executes by evaluating all key stimuli of said stimuli-behavior pairs, running the first said stimuli-behavior pair having a said key stimuli which is set, and running said default behavior if no said key stimuli is set.

23. The method of claim 19, wherein:

specifying of said decision type behavior further includes specifying a set of probable behaviors by choosing at least one behavior; wherein

said decision type behavior executes by picking in a random manner one member of said set of probable behaviors, and running said behavior.

24. The method of claim 23, further including:

influencing the probability of members of said set of probable behaviors being executed by specifying a weighting factor for at least one of said probable behaviors.

* * * * *